

SNe Ia : Sondes pour l'Énergie Noire

N. Regnault

(LPNHE, Paris)

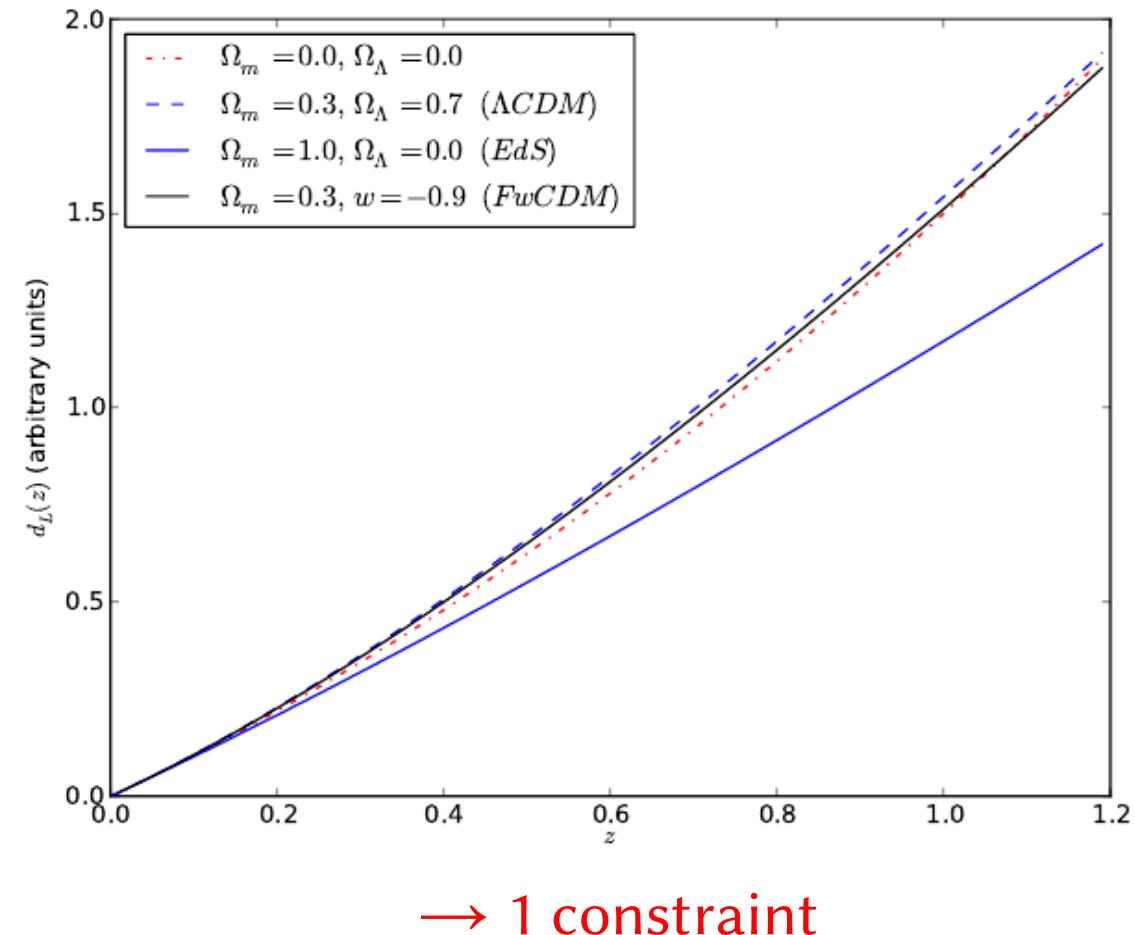
OUTLINE

- Mapping the expansion history with SNe Ia
- Recent progress : statistics + control of systematics
 - Statistics
 - Photometric calibration
 - Light curve fitters (SN Ia empirical models)
- Recent results : JLA
- Perspectives

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STANDARD CANDLES IN COSMOLOGY



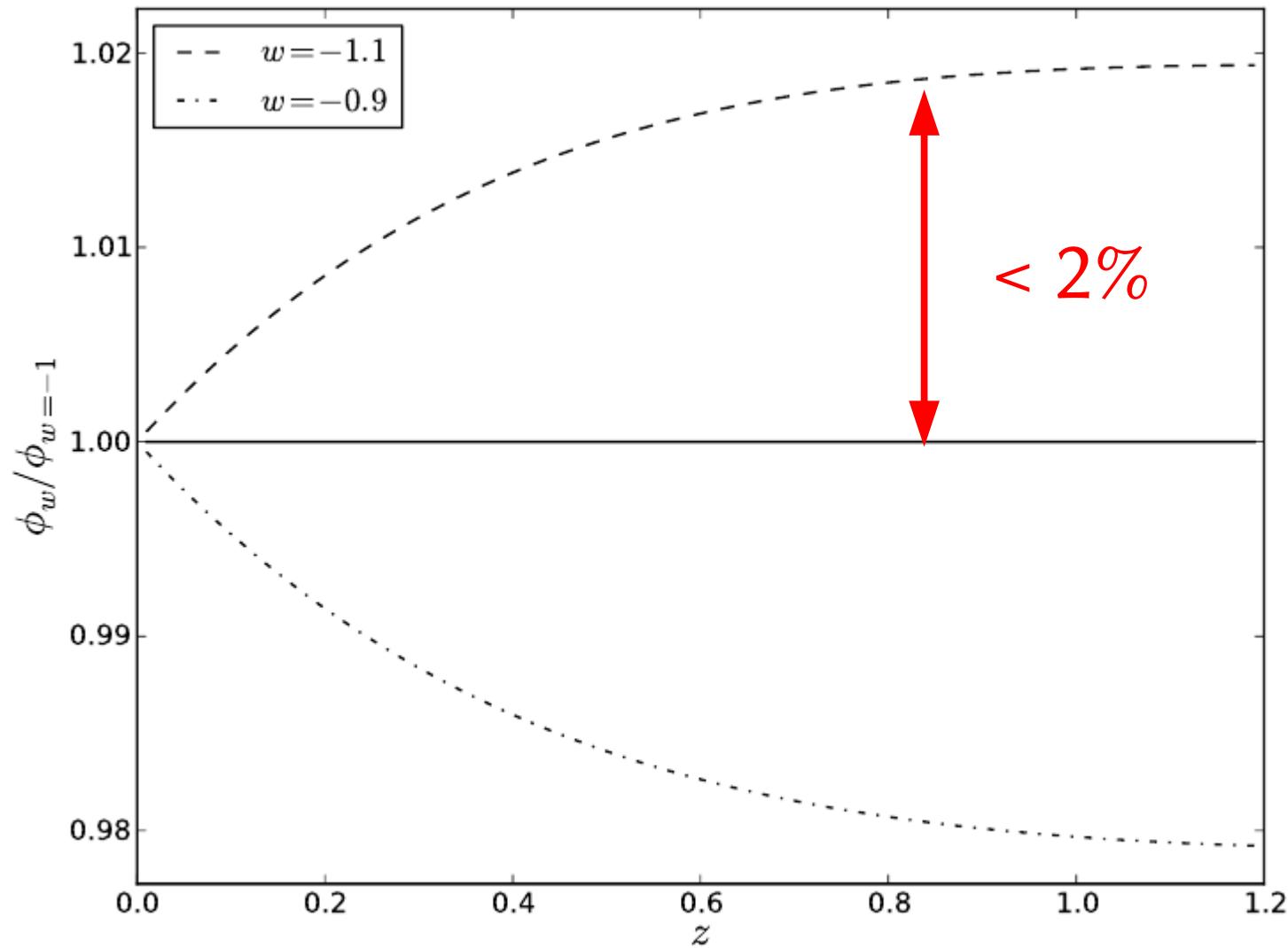
- Observables
 - Redshift $z = \delta\lambda/\lambda$
 - Apparent flux
- Standard candles
- Integrated history of expansion

$$f = L / 4\pi d_L^2(z)$$

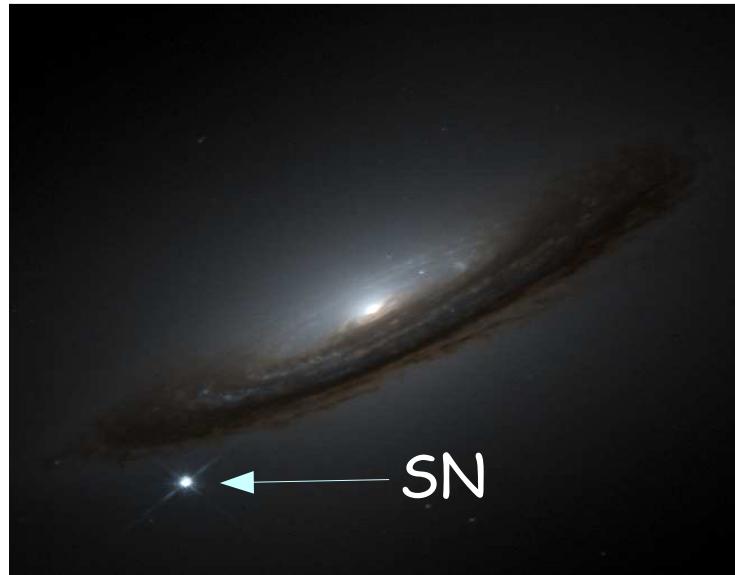
$$\propto \int \frac{dz}{H(z)}$$

$$d_L(z) = (1+z) \frac{c}{H_0} \int dz' \left(\Omega_m (1+z)^2 + \Omega_X (1+z)^{3(1+w)} \right)^{-1/2}$$

MEASURING w

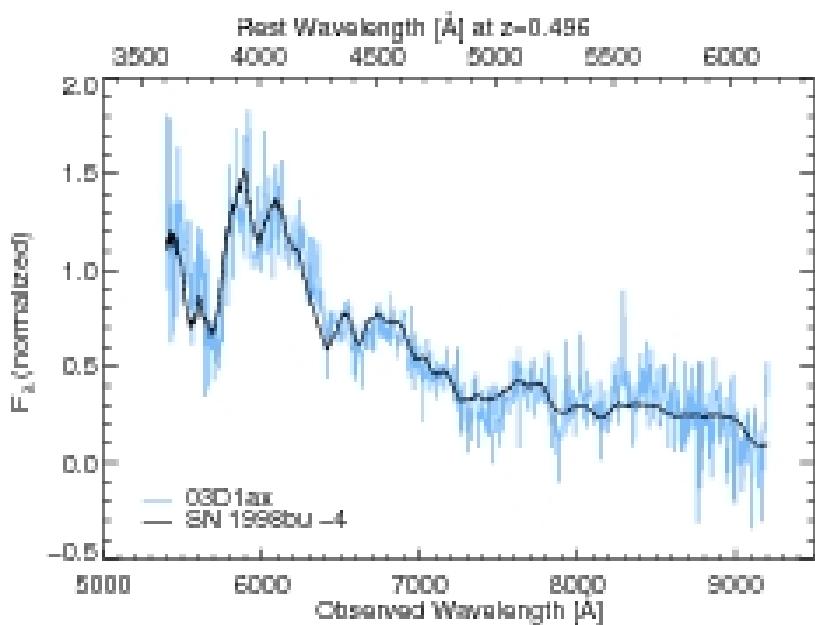


TYPE Ia SUPERNOVAE



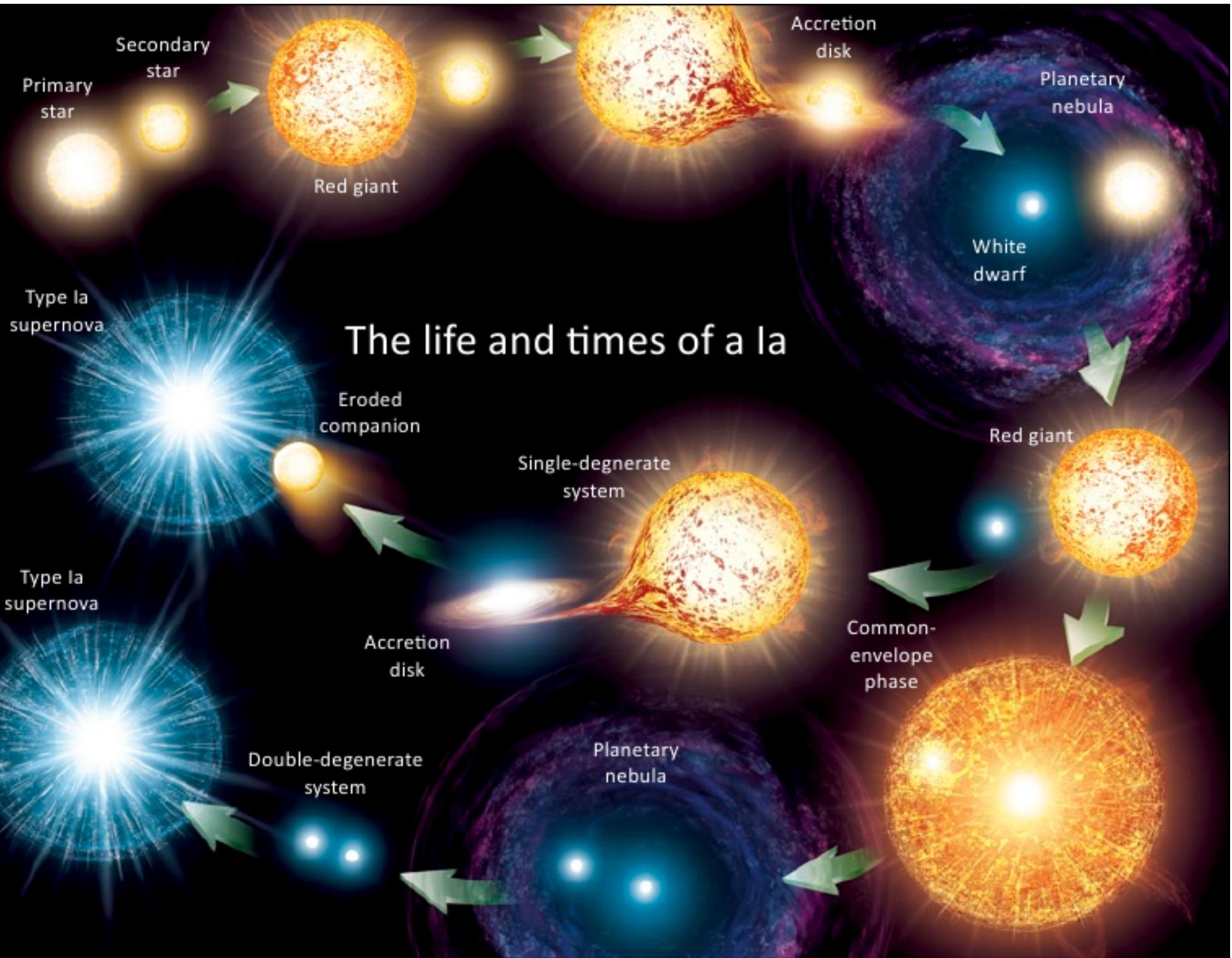
- Thermonuclear explosion of WD
 - Rare events ($\sim 1 / \text{Gal} / 1000 \text{ yr}$)
 - Very bright ($\sim 10^{10}$ solar luminosities)
 - Transients ($\sim 1 \text{ month}$)
 - $\sigma(L_{\max}) \sim 40\%$

Standardizable $\rightarrow \sigma(L_{\max}) \sim 15\%$

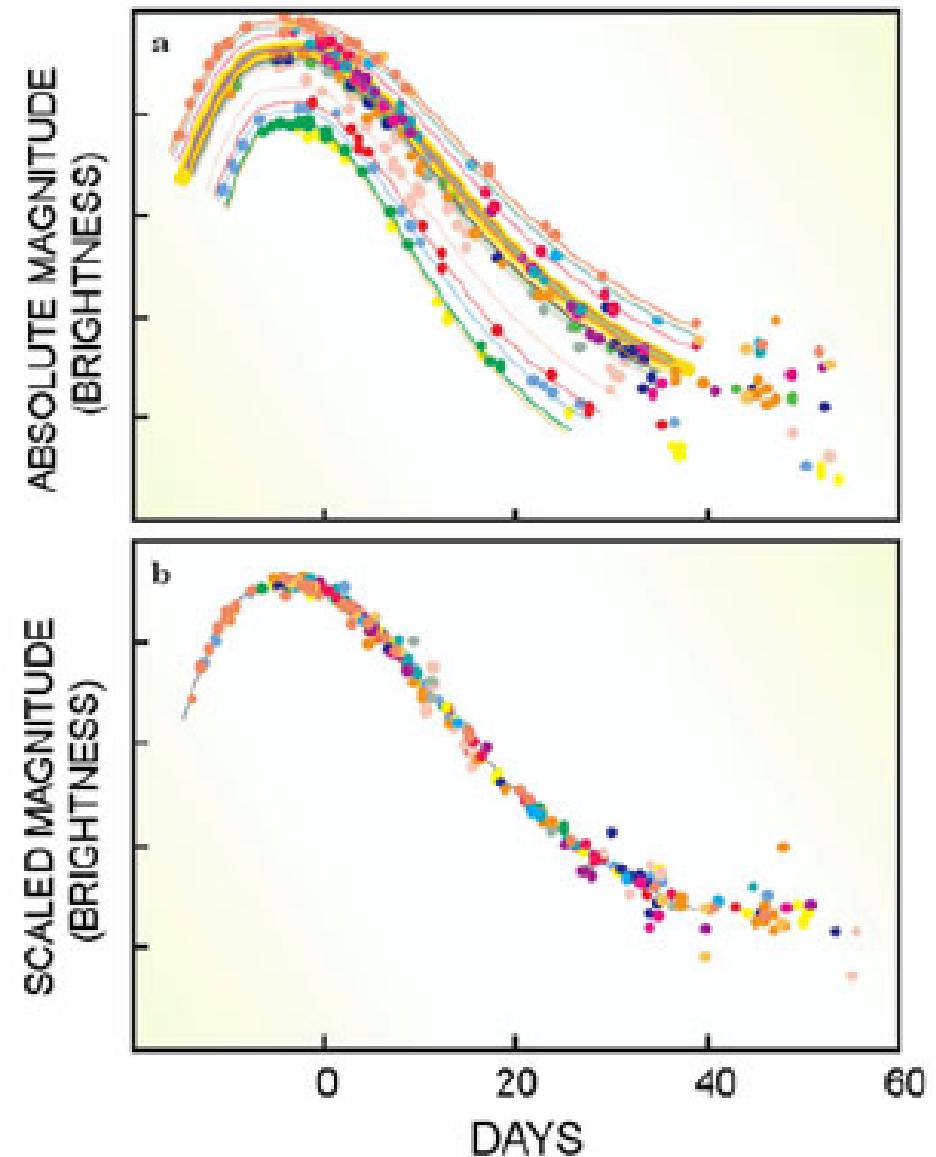
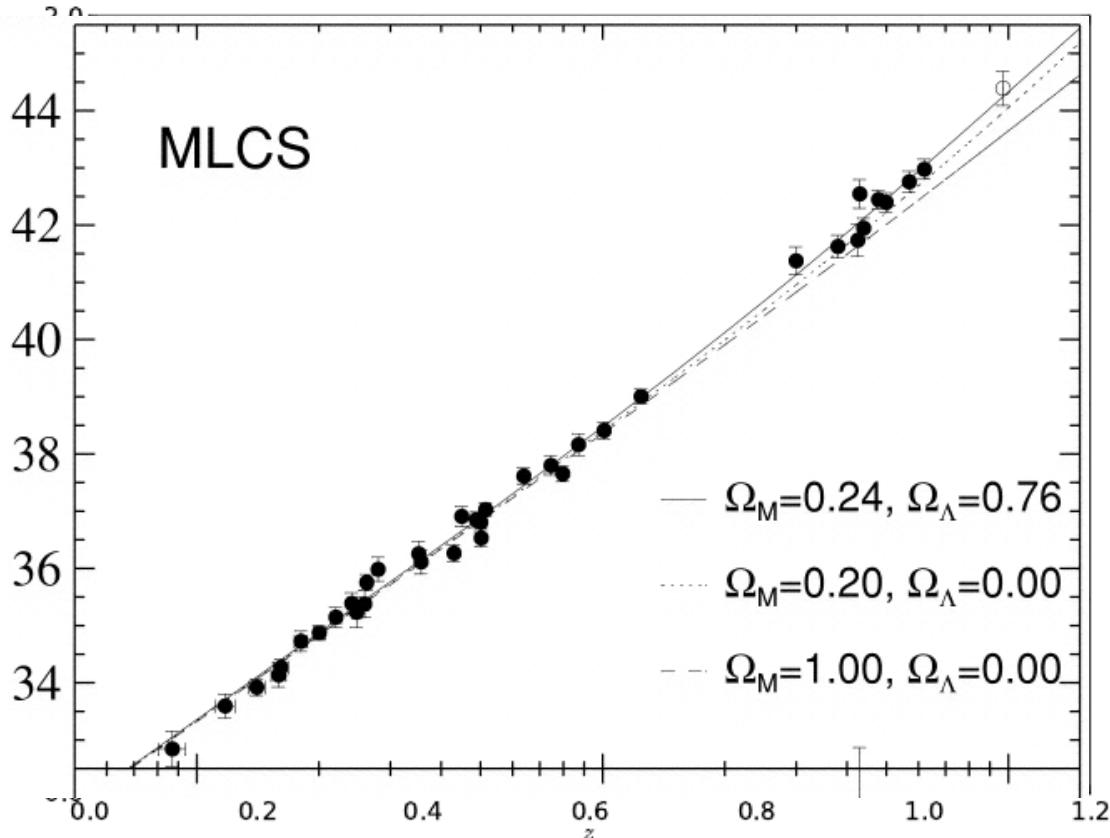


- Spectroscopy
 - Identification (broad features)
 - Chemical composition & velocities

Hillebrandt & Niemayer, 2000
Maoz et al, 2014

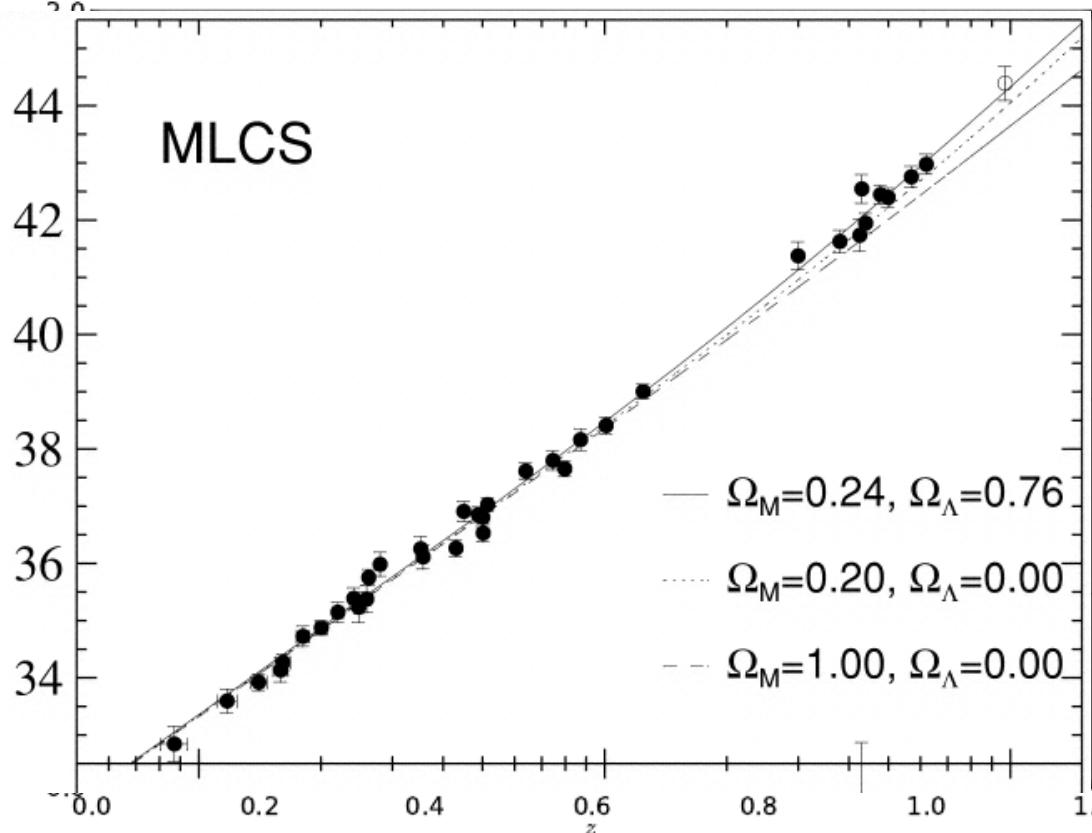


MAPPING THE EXPANSION WITH SNe Ia



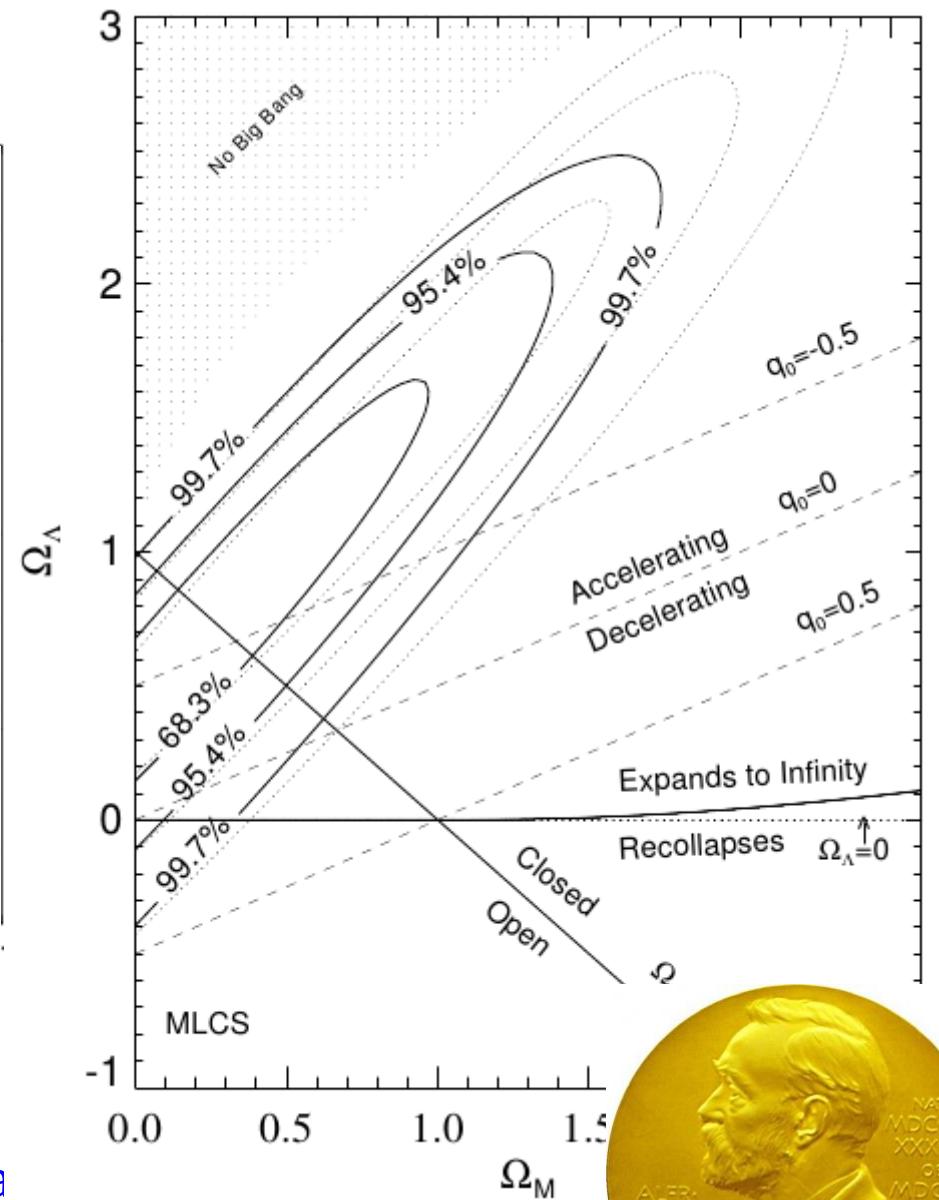
- Probe of the expansion history
 - Independent of the CMB
 - Very complementary for Dark Energy studies

MAPPING THE EXPANSION WITH SNe Ia



First (convincing) evidence for acceleration

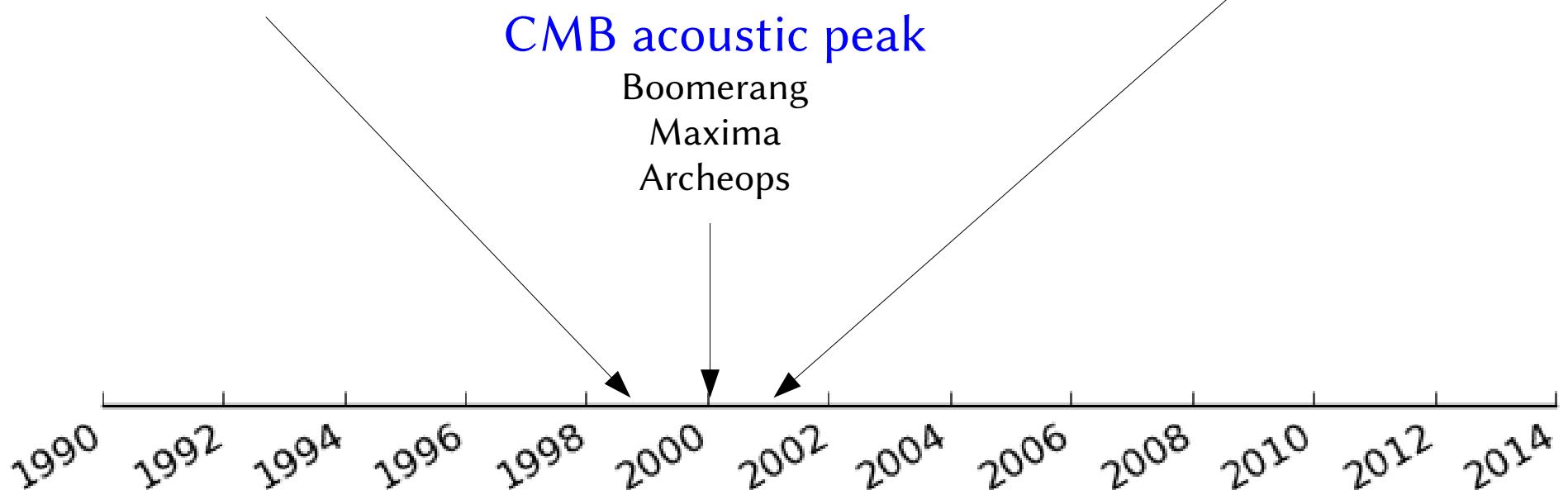
$$\rightarrow \Lambda > 0$$



Acceleration of the Expansion

Riess et al '98
Schmidt et al '98
Perlmutter et al '98

H_0 from HST
Freedman et al, 2001



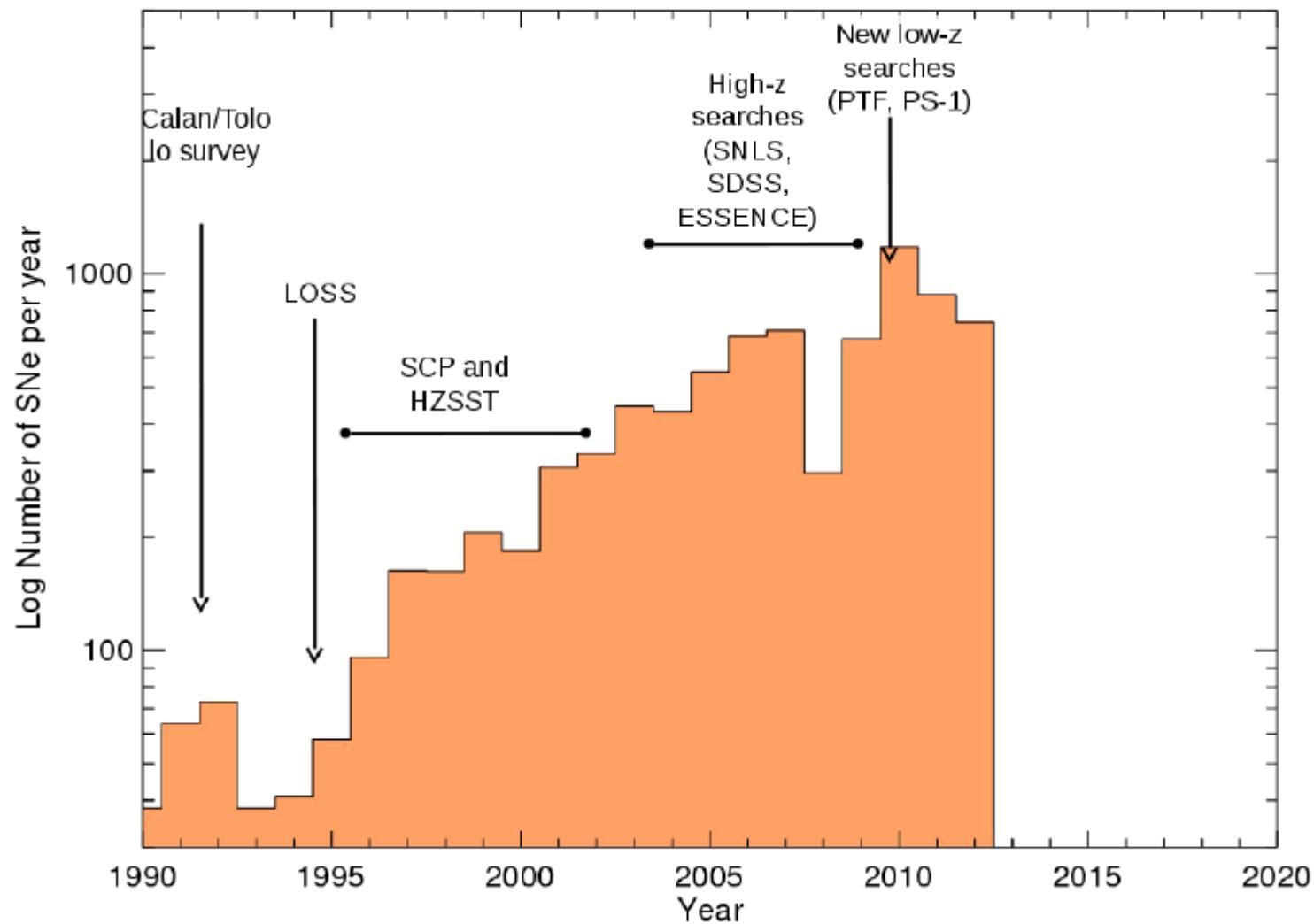
.. hints for a low Ω_m
(Efstathiou et al, 1990)
(Peacock, 1991)
(Bahcall & Fan, 1998)
...

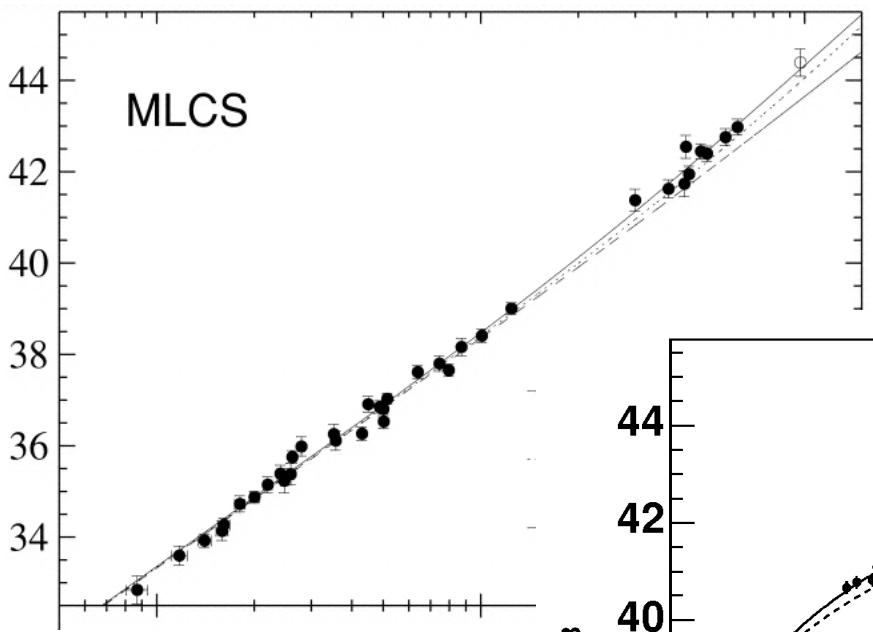
Precision measurements :
WMAP
Planck
SDSS
SNLS
BOSS

OUTLINE

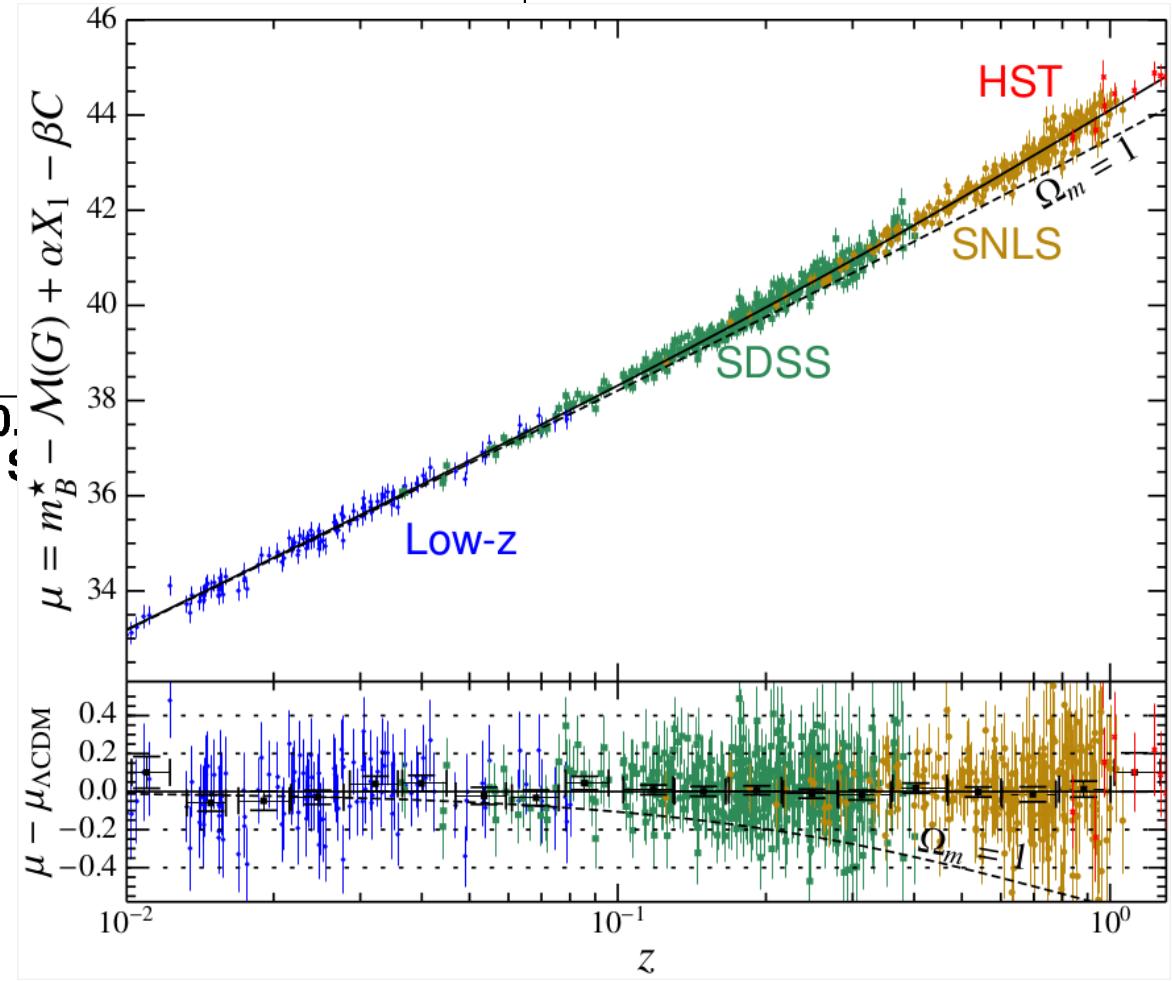
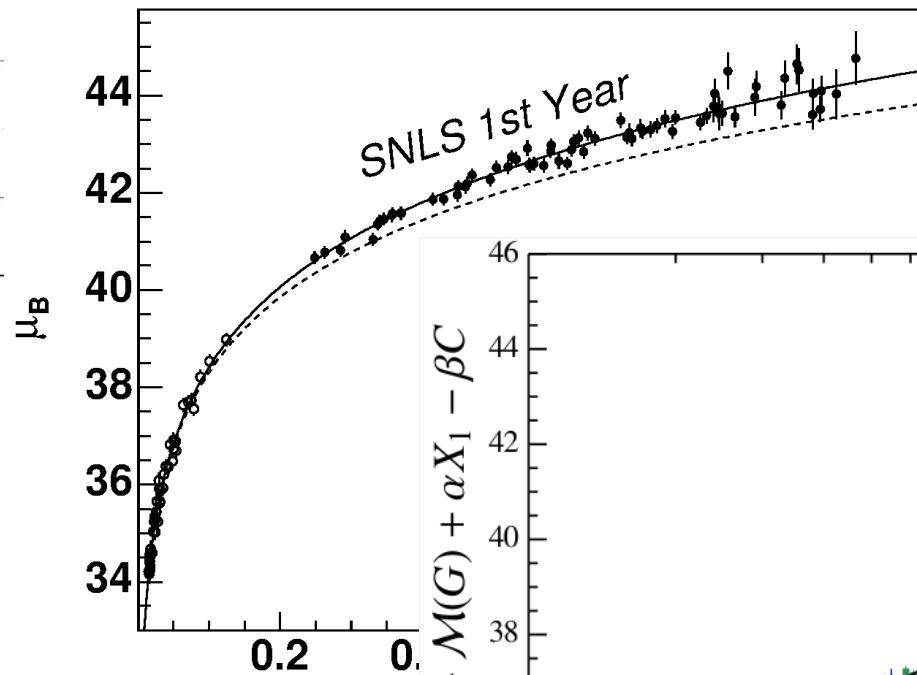
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DISCOVERY RATE

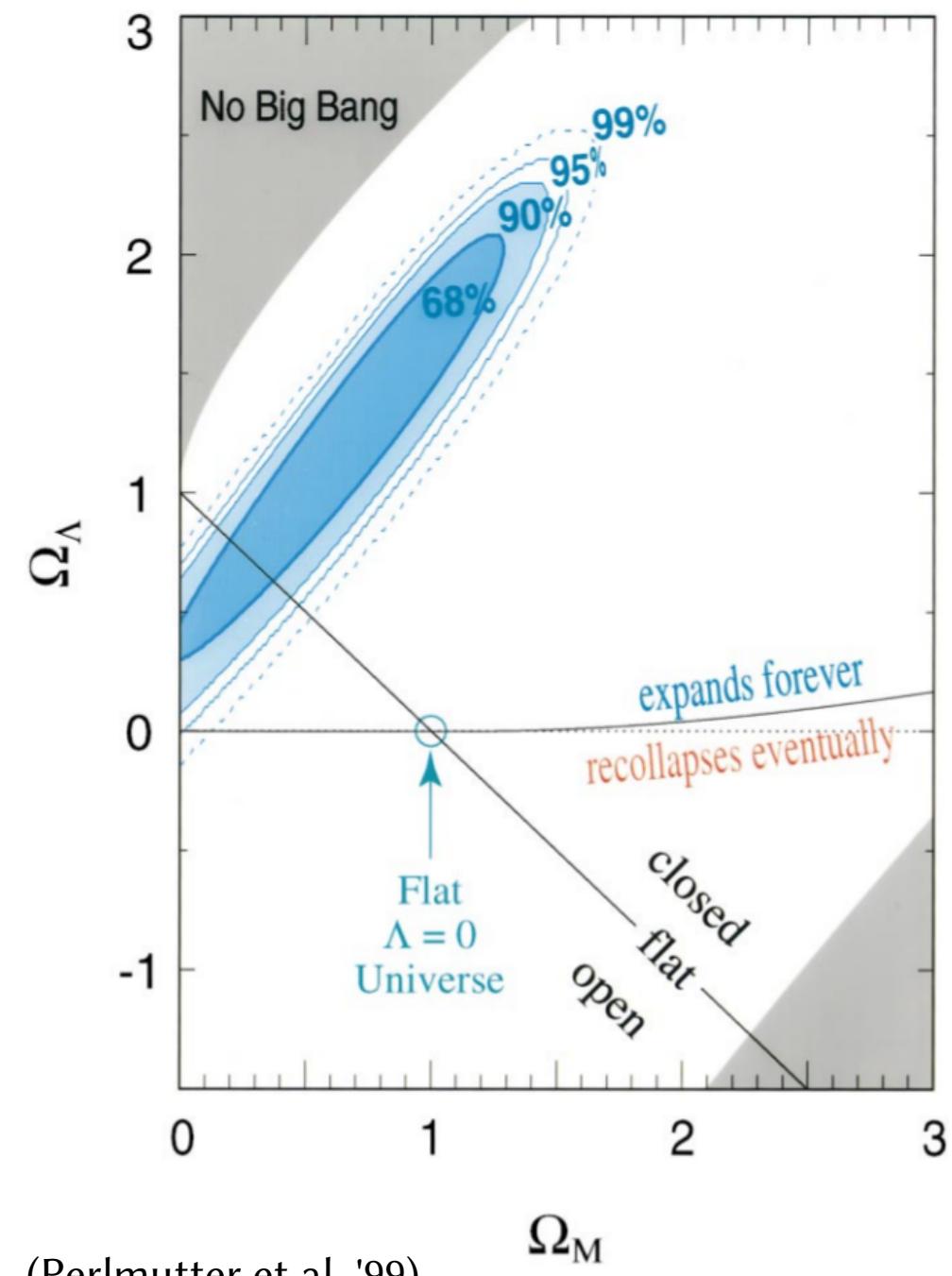




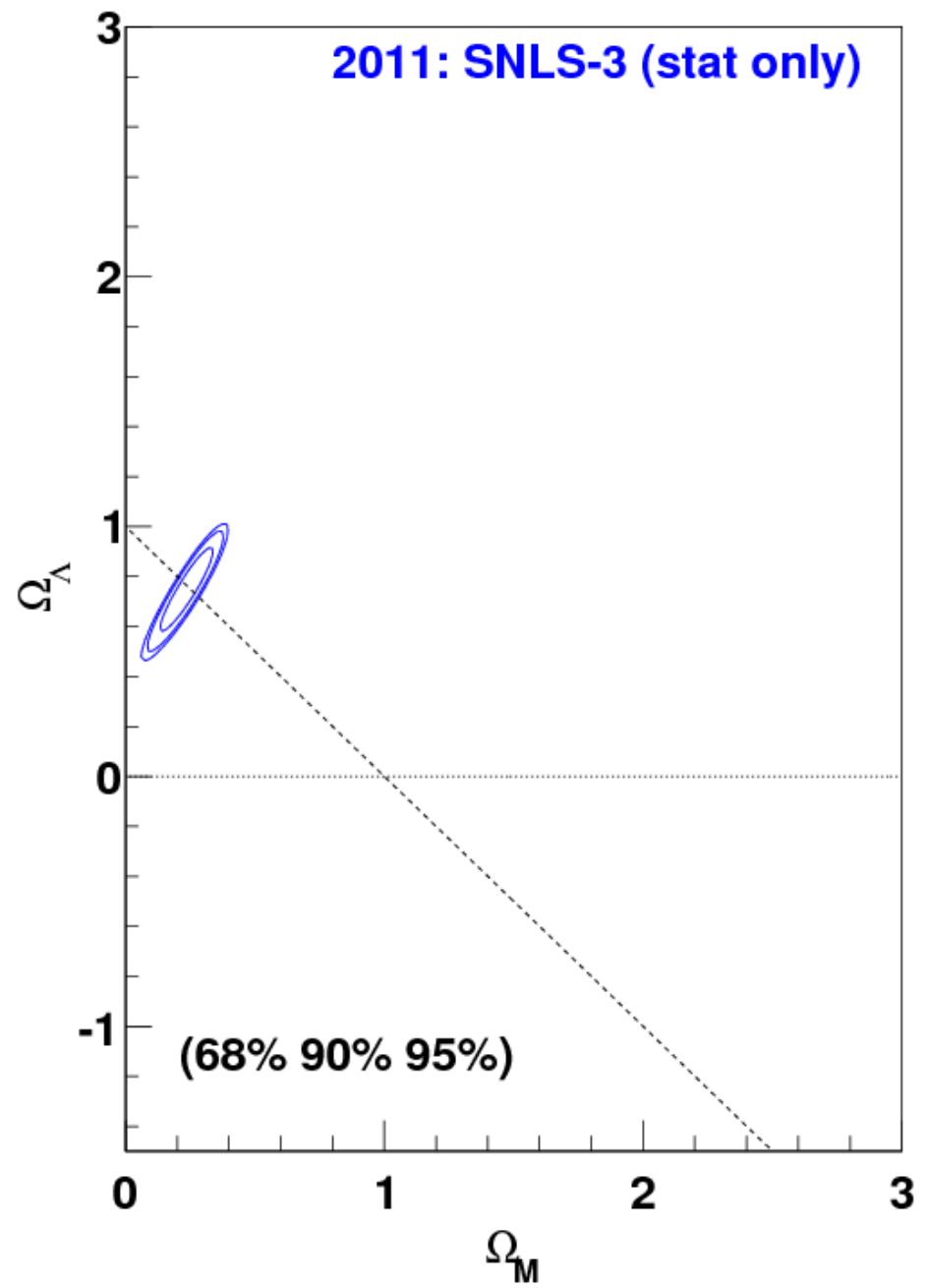
STAT X 20 IN 10 YEARS



- 1998 : O(50) SNe
- 2005 : O(100) SNe
- 2014 : O(1000) SNe
(x 20 in statistics)



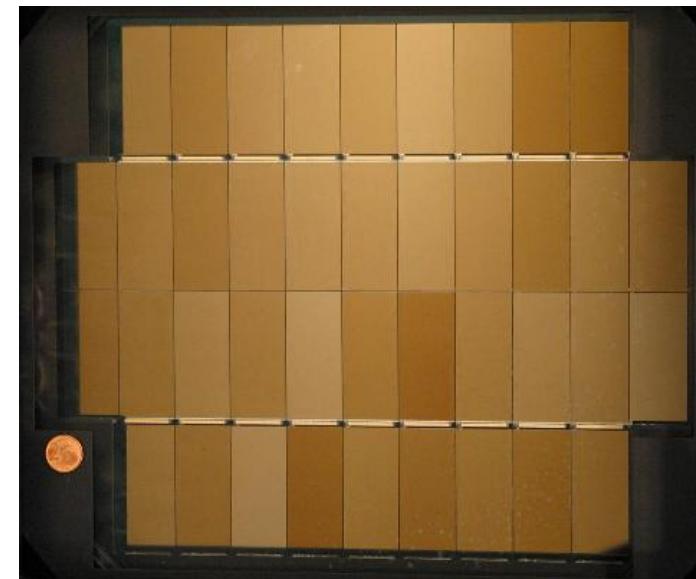
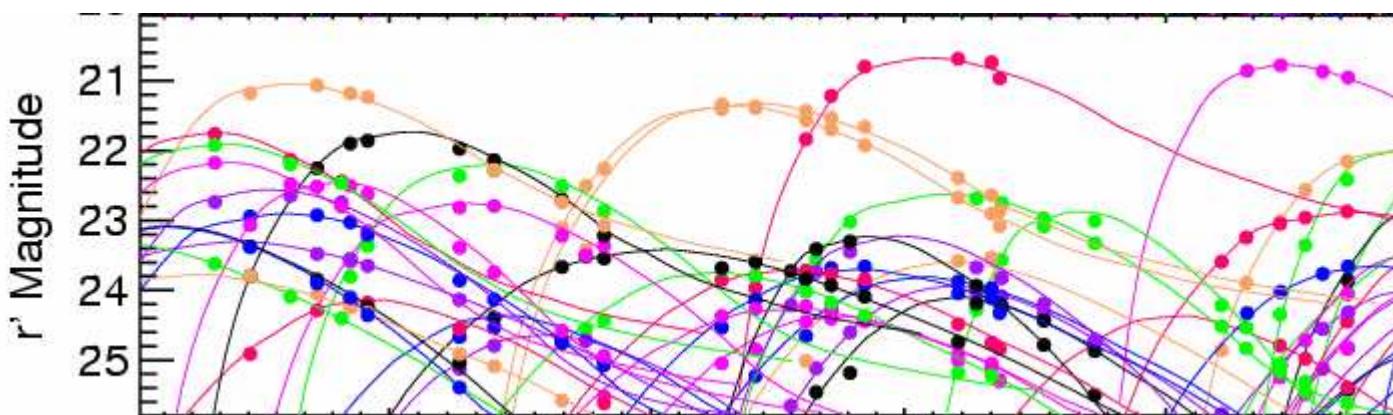
(Perlmutter et al, '99)



(Conley et al, '11, Sullivan et al, '11, Guy et al '10)

ROLLING SEARCH

Rolling searches on large CCD mosaics

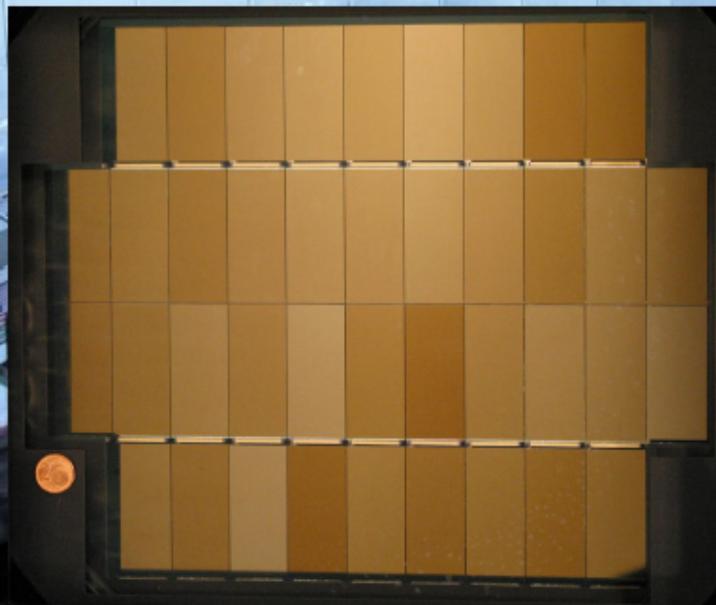


Observing steps:

- Discovery in image subtraction ← From the same images !
- Spectroscopic ID
- Measure light curves
- Get an image without the SN ← Implemented on 3 major surveys
... with “classical spectroscopy”

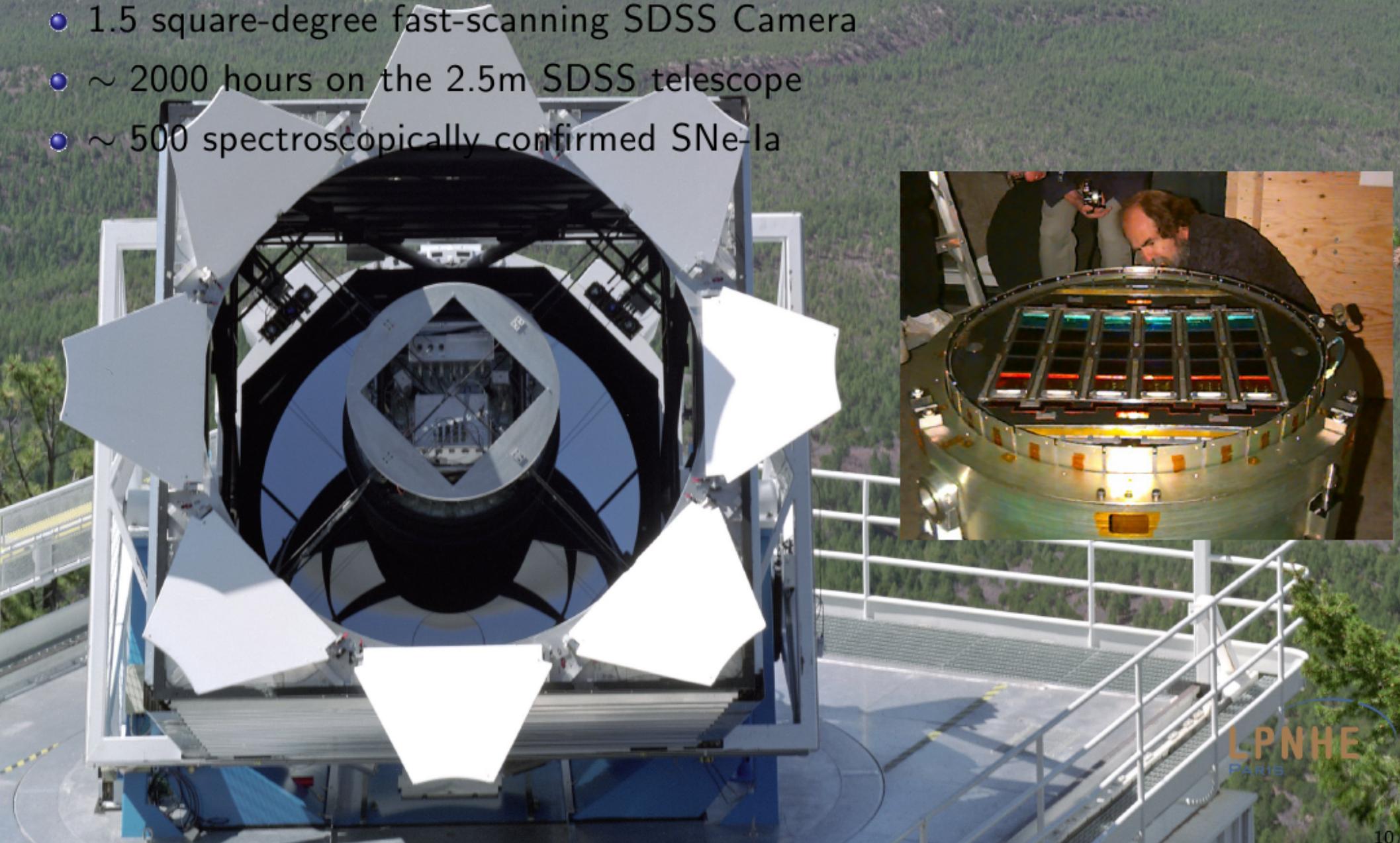
The Supernovae Legacy Survey (Astier et al. 2006)

- 1 square degree MegaCam camera
- 1500 h on the CFHT 3.6m
- Spectroscopic follow-up: ~1500h on 8m VLT-Keck-Gemini
- ~ 500 spectroscopically confirmed SNe-Ia

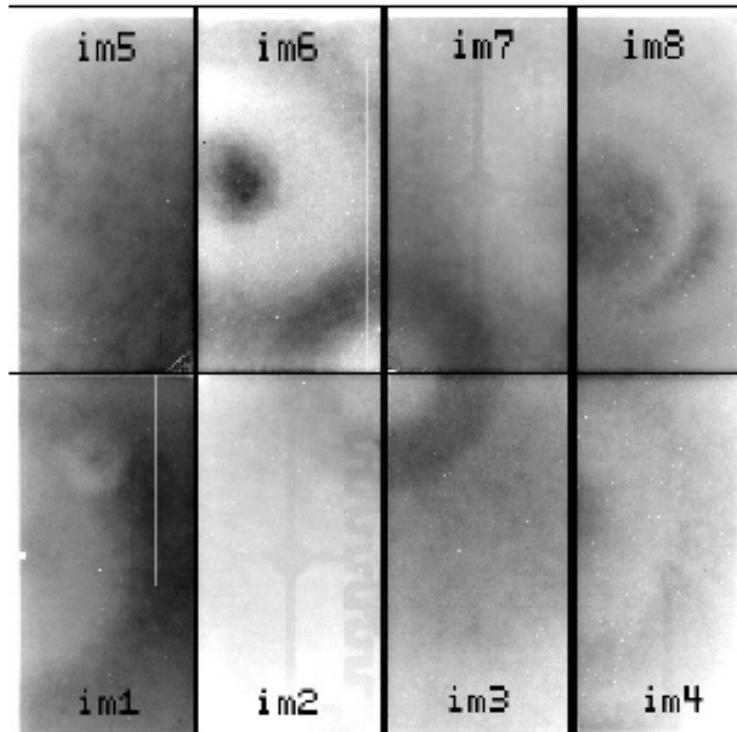


The SDSS-II Supernovae Survey (Kessler et al. 2009)

- 1.5 square-degree fast-scanning SDSS Camera
- \sim 2000 hours on the 2.5m SDSS telescope
- \sim 500 spectroscopically confirmed SNe-Ia

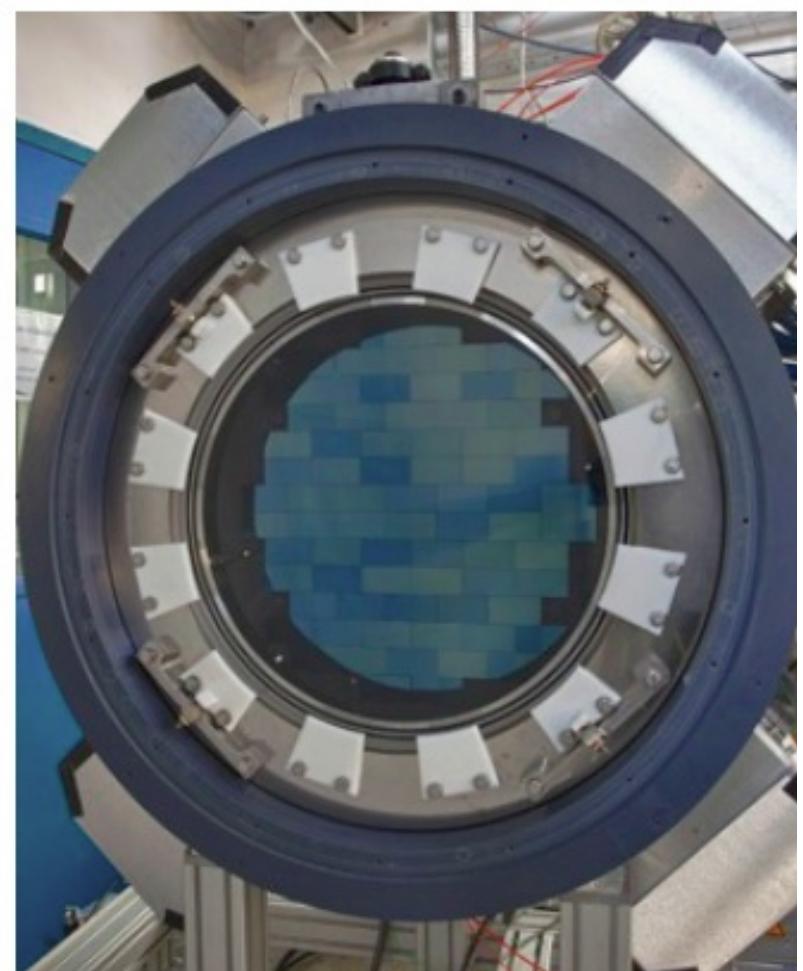
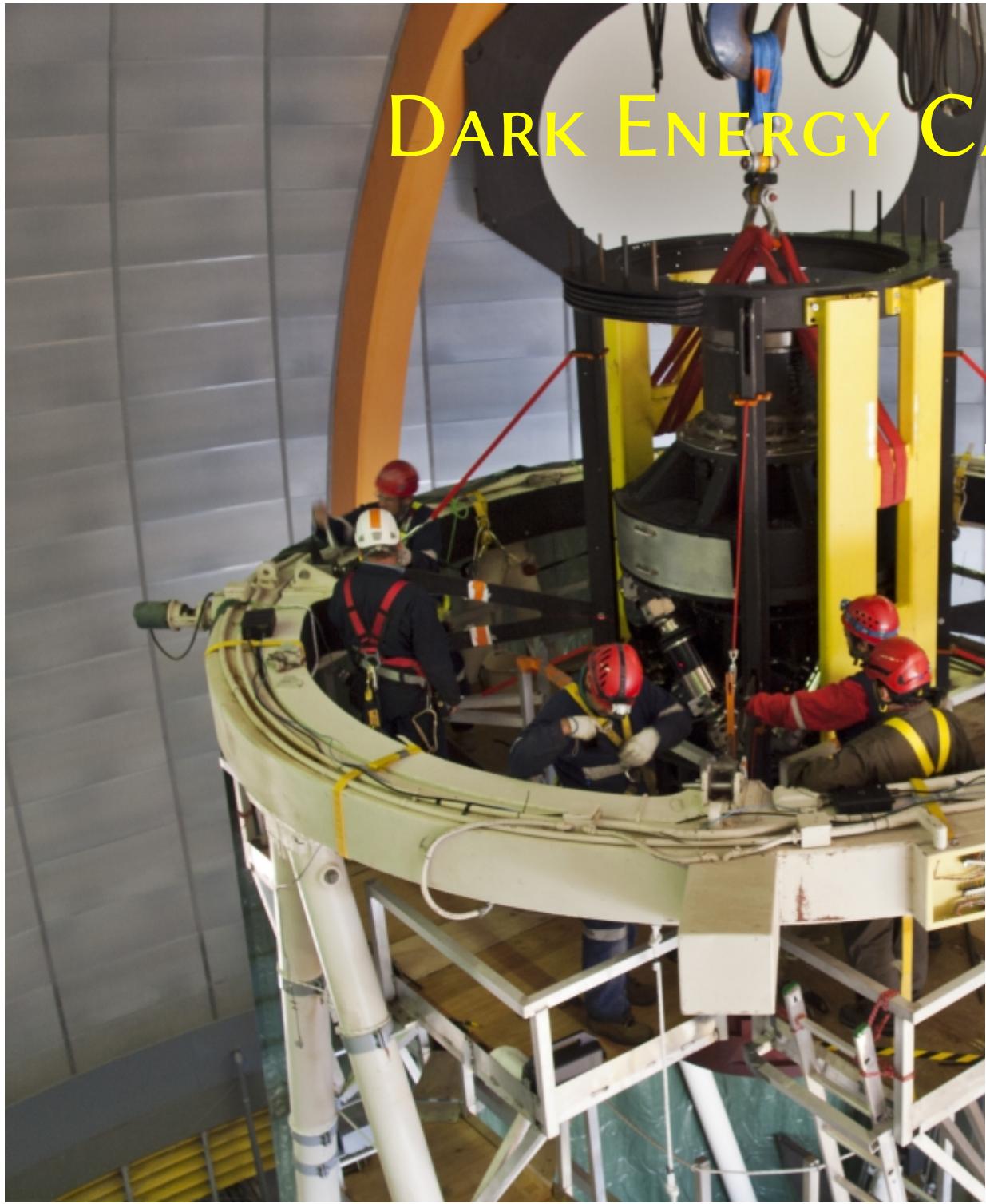


ESSENCE (WOOD-VASEY ET AL, '07)

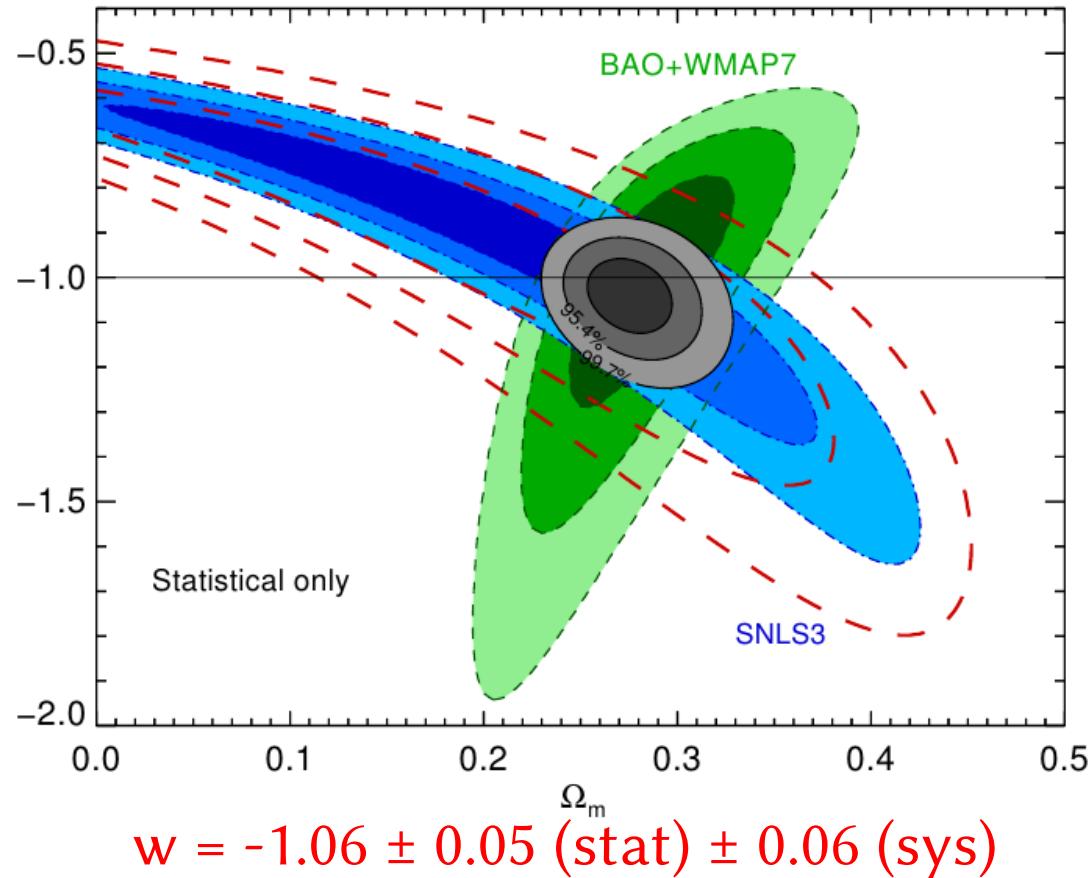


- CTIO Blanco 4m telescope
- $36' \times 36'$ Mosaic camera
- ~ 100 SNe-Ia

DARK ENERGY CAMERA



SYSTEMATICS



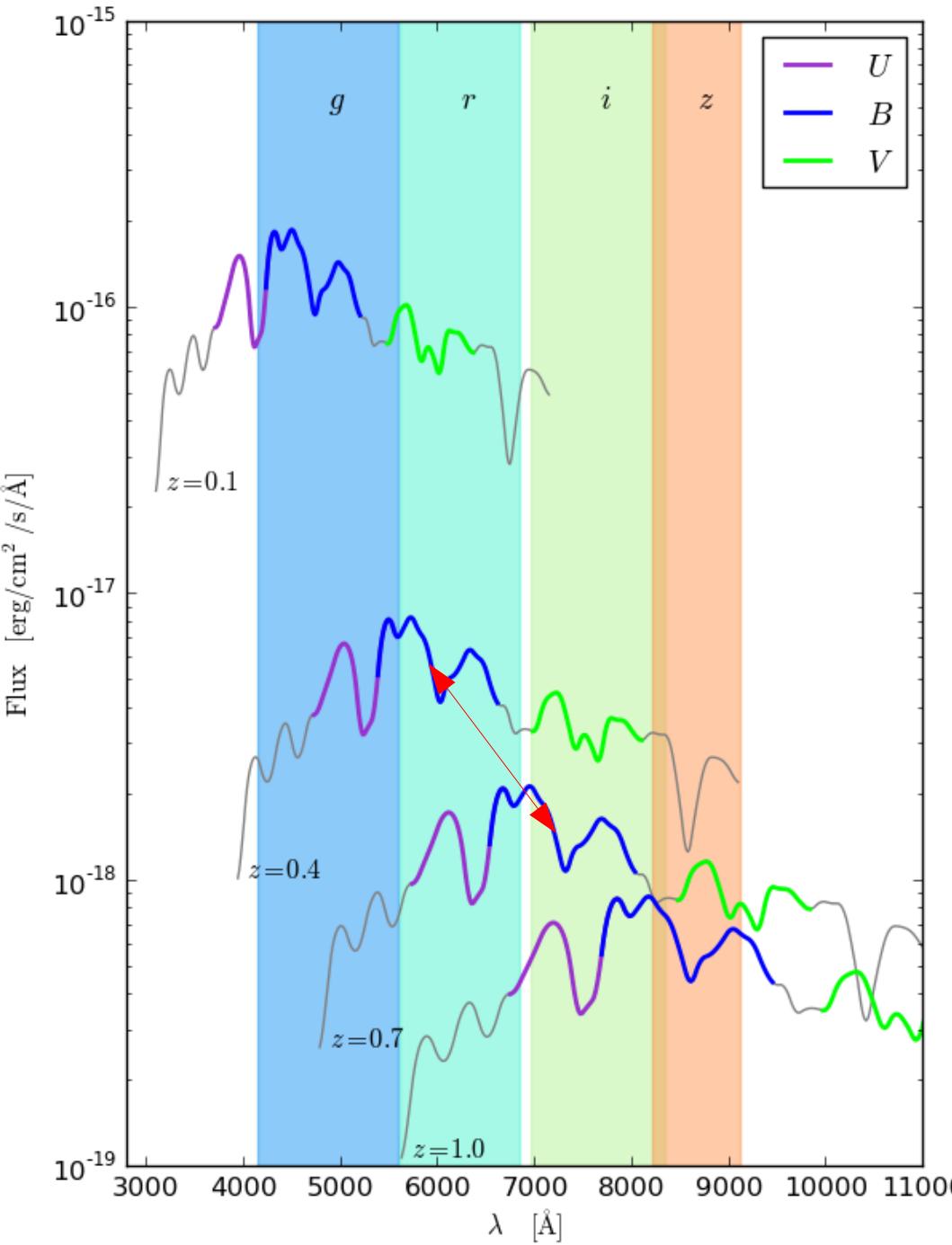
- SNLS3 analysis
(Guy et al, '10, Conley et al, '11, Sullivan et al, '11)
- Systematic uncertainties
 - ~ half of the error budget
 - mostly photometric calibration

Priority : controlling the systematics

OUTLINE

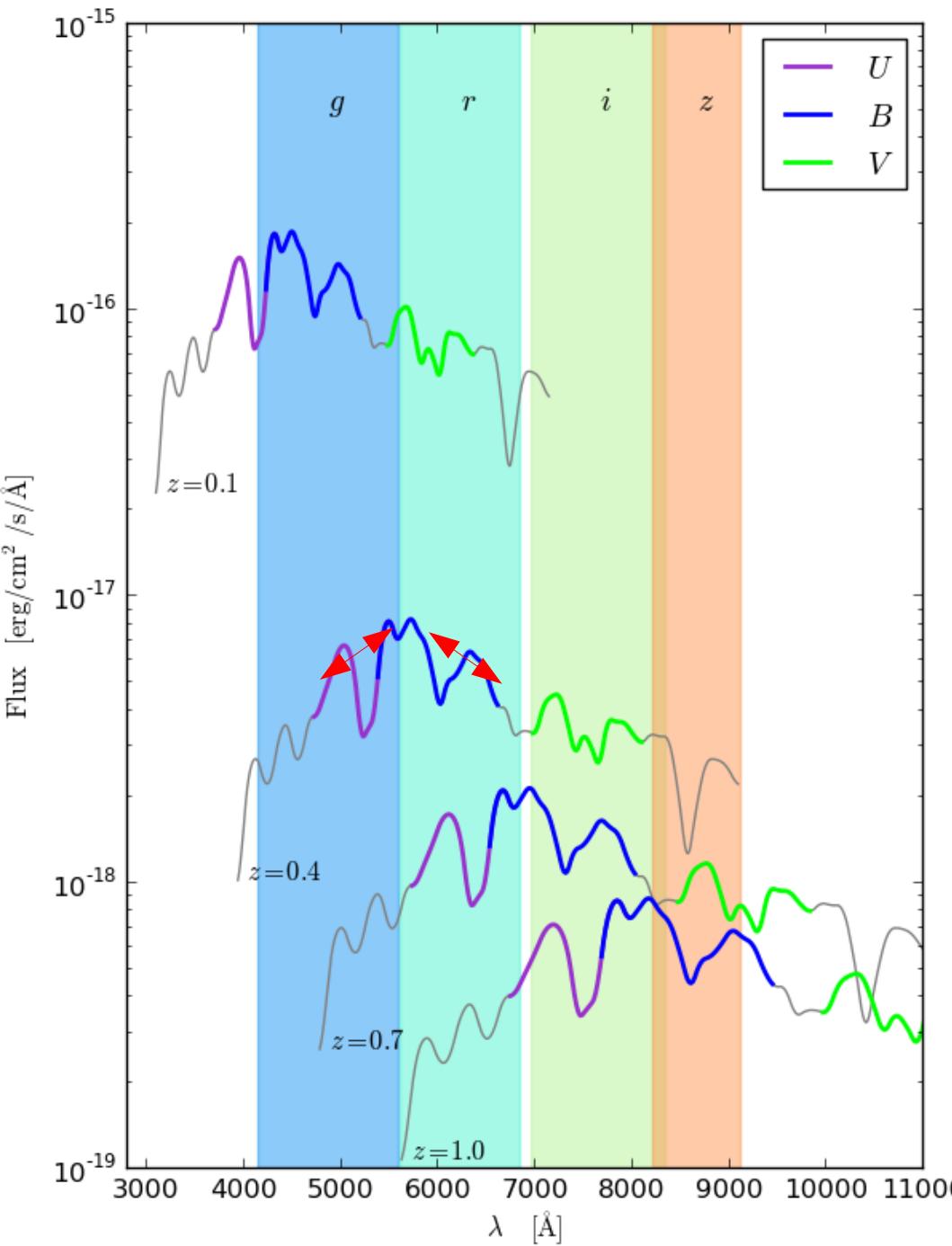
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SYSTEMATICS

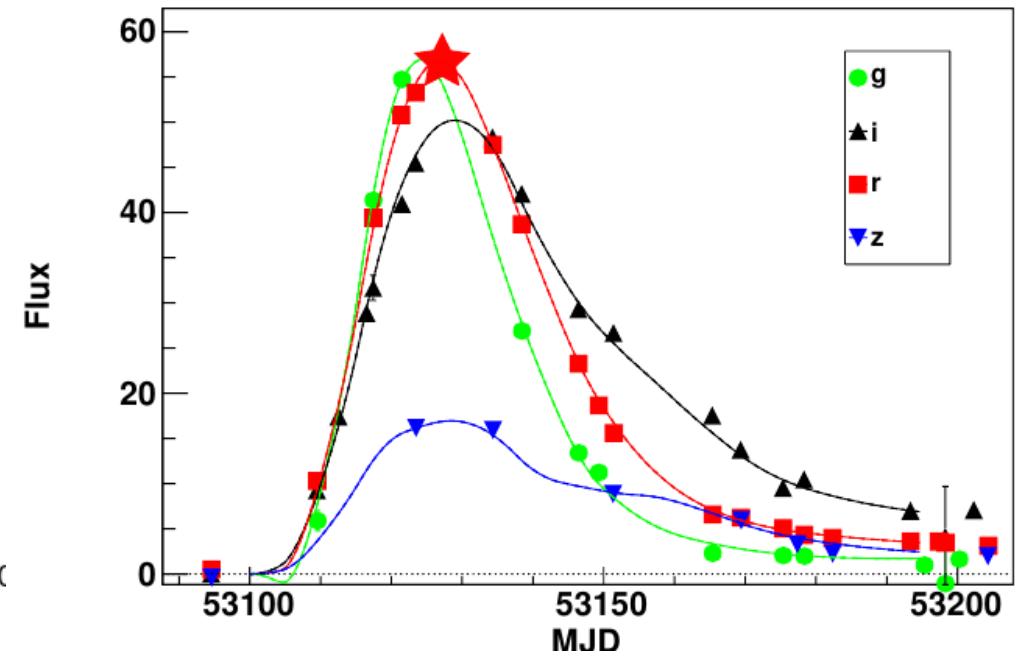


- Ingredients
 - Flux ratios between (observer) bands
→ (relative) flux calibration

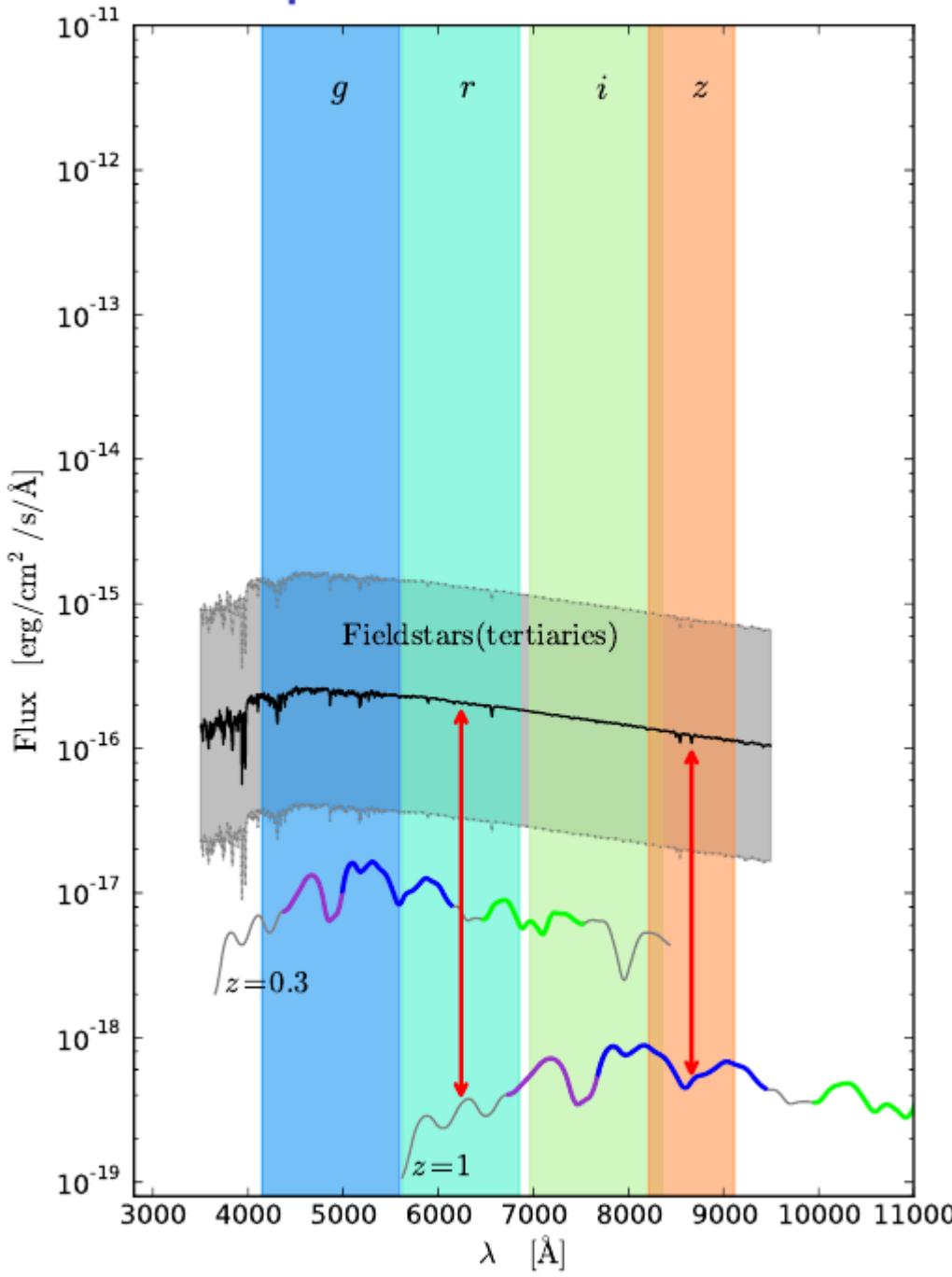
SYSTEMATICS



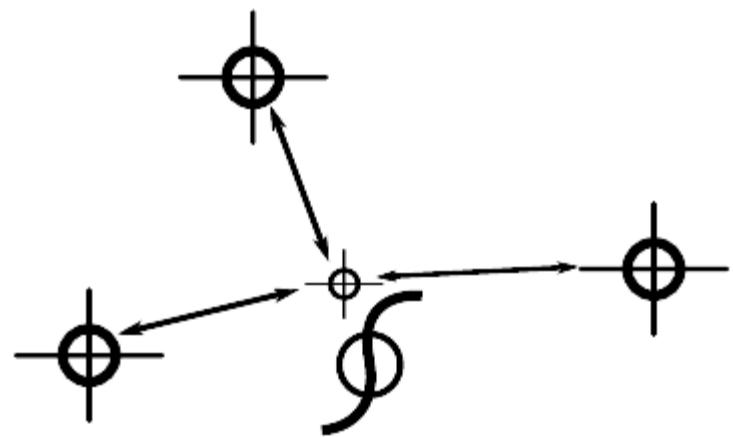
- Ingredients
 - Flux ratios between (observer) bands
→ (relative) flux calibration
 - Interpolate in time and wavelength
→ Light curve model



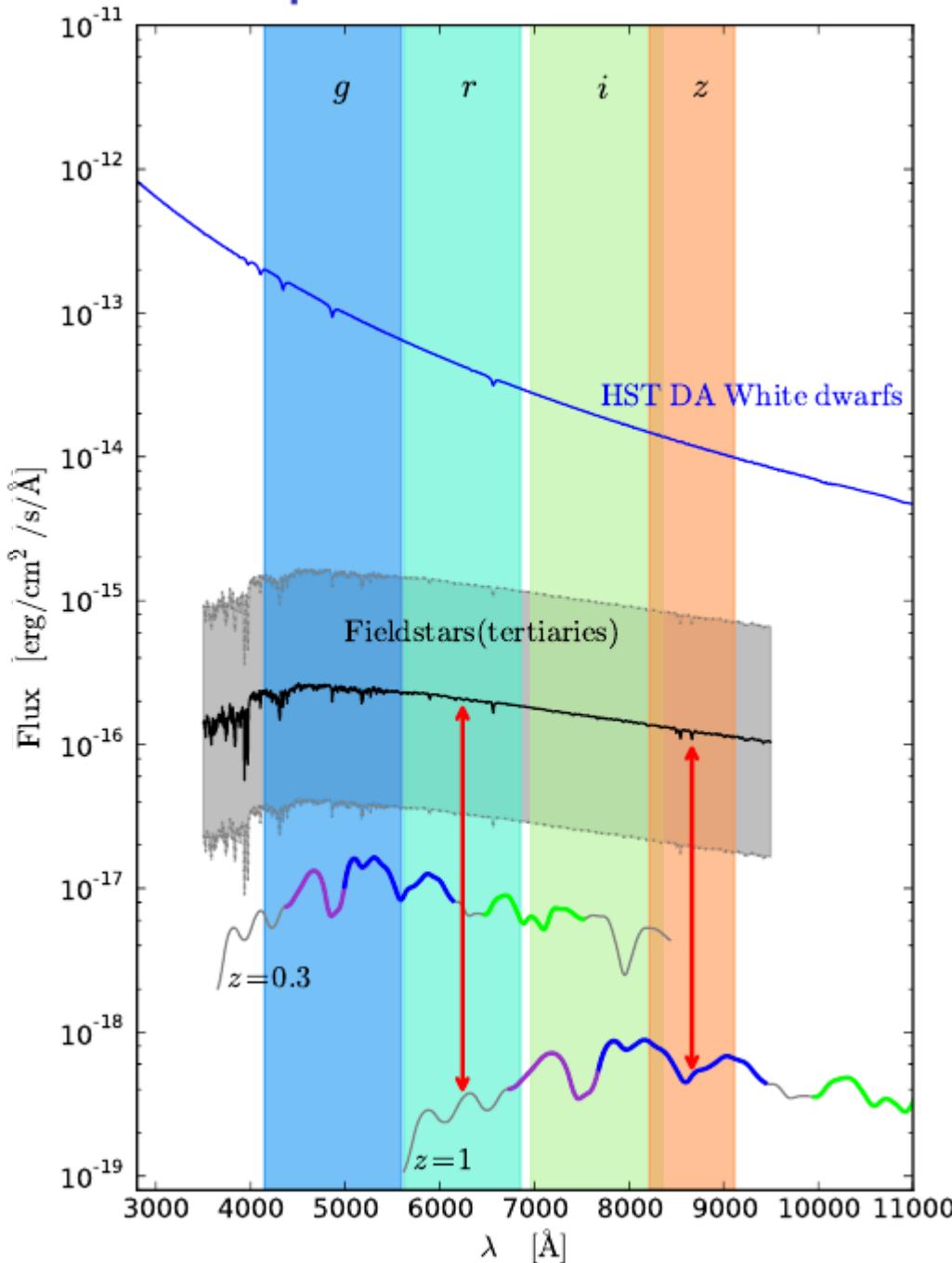
PHOTOMETRIC CALIBRATION



- Instrument response
 - Measure flux ratios in a single image

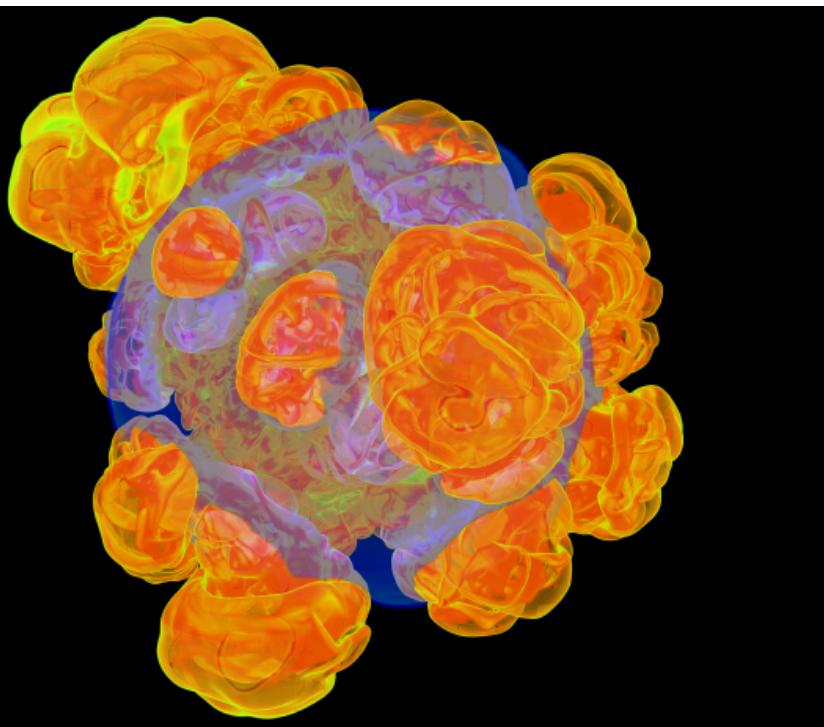


PHOTOMETRIC CALIBRATION

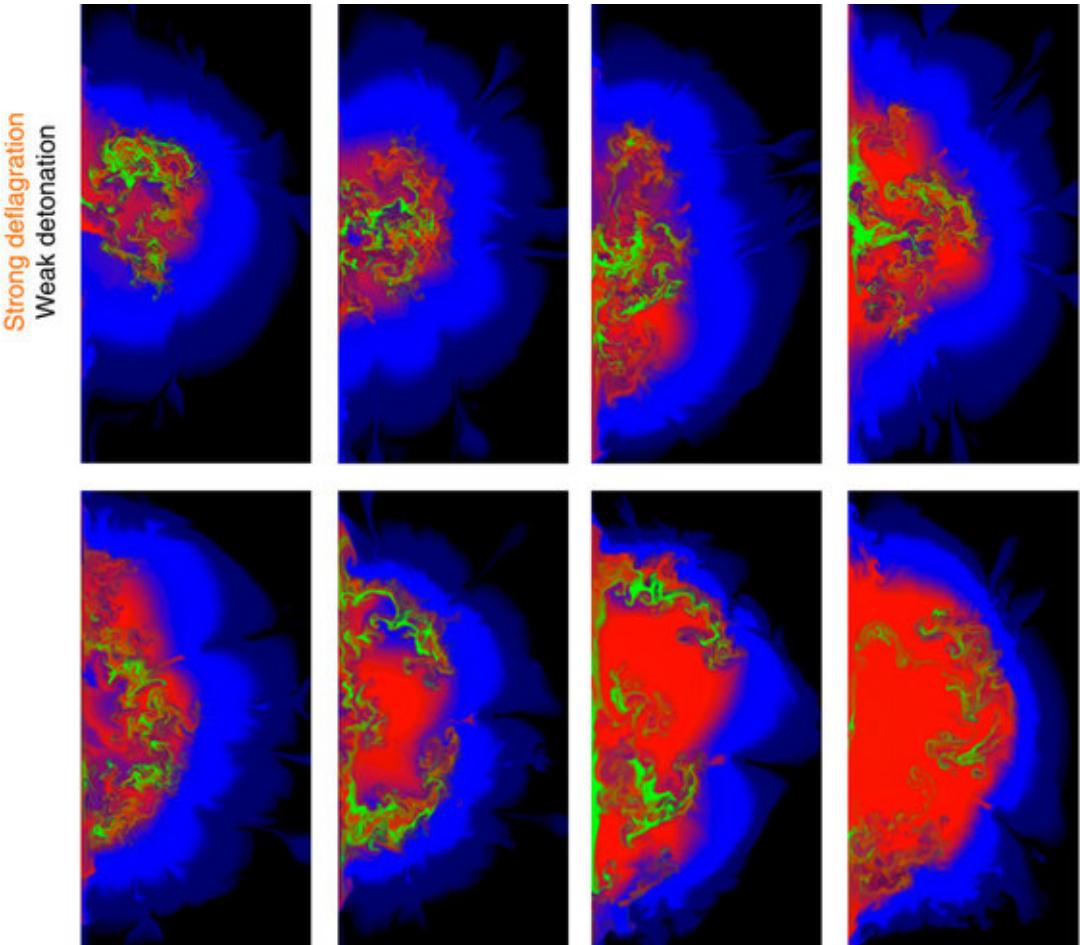


- Instrument response
 - Measure flux ratios in a single image
 - Calibration transfer
 - HST standard as a primary calibration flux
-
- A diagram showing three circular targets with crosshairs. Arrows indicate a flow from the top target to the middle one, and from the middle one to the bottom one. A large, stylized arrow points from the bottom target towards the right, representing the transfer of calibration from a primary standard (HST) to a secondary standard or target object.

SNIA MODELS



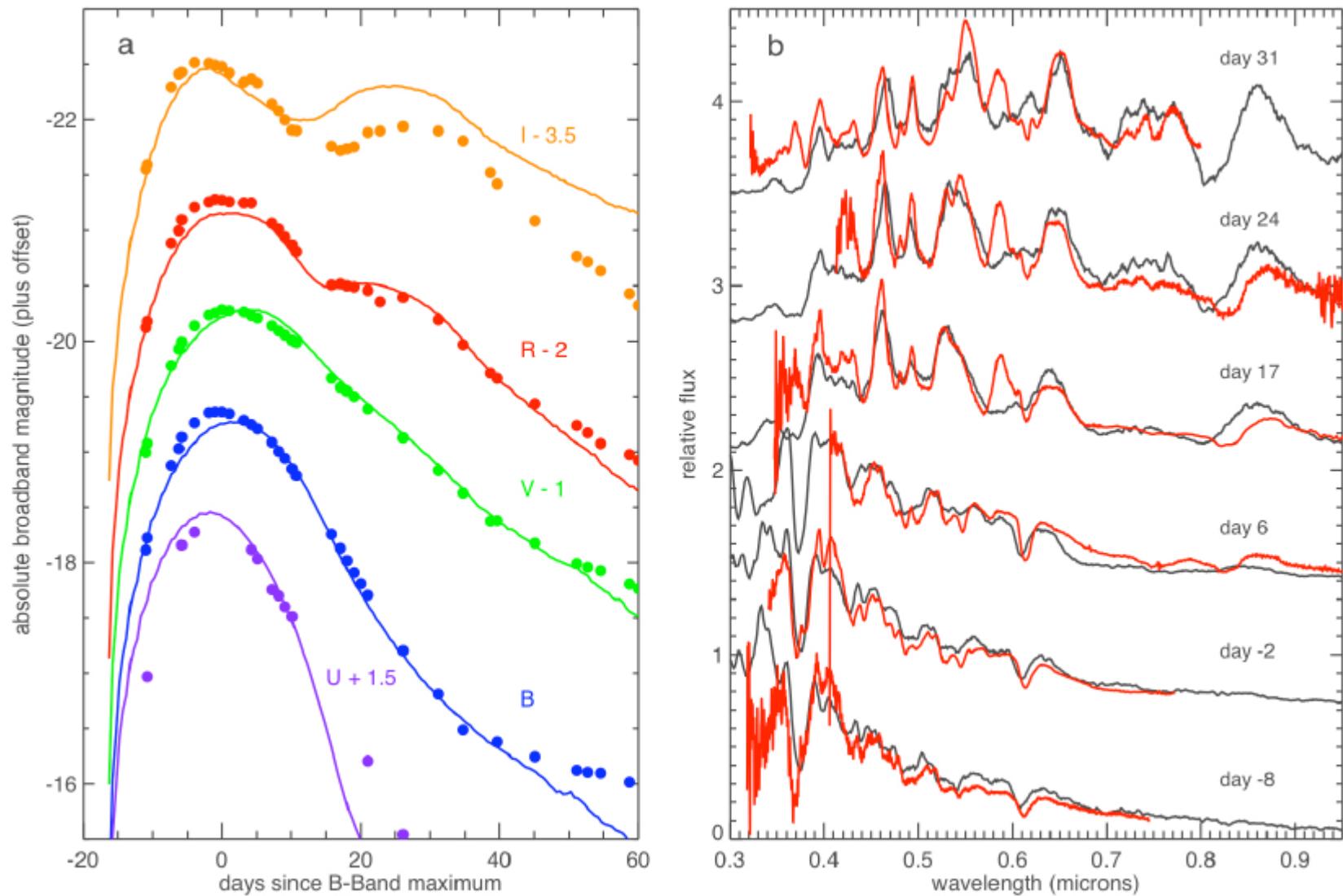
Jordan et al, astro-ph/0703573



Kasen et al, 0907.0708

- Thermonuclear explosion of C/O white dwarf fed by companion star
- Lots of non-linear physics going on...

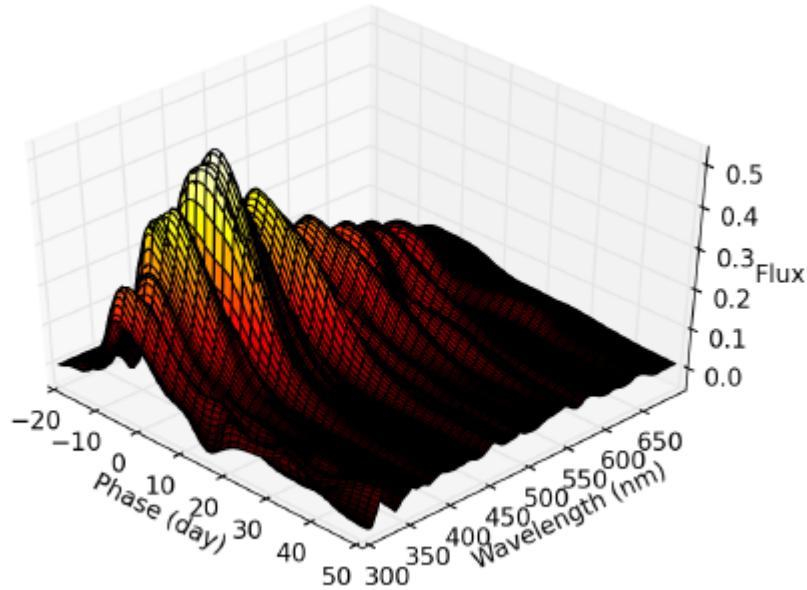
QUALITATIVE AGREEMENT WITH DATA



Kasen et al, 0907.0708

Not accurate enough to measure distances

SN LIGHTCURVE MODELS



- Other techniques
 - MLCS, MLCS2k2 (e.g. Jha et al, 2007)
 - SiFTO (Conley et al, '08)
 - BATM ...
- SALT2 (Guy et al, '05, '07)
- Empirical, spectrophotometric model of SNe Ia
- Fitted on spectroscopic & photometric data (aka “training sample”)
- Surface shape parametrized by 3 parameters (m_b , X_1 & c)

OUTLINE

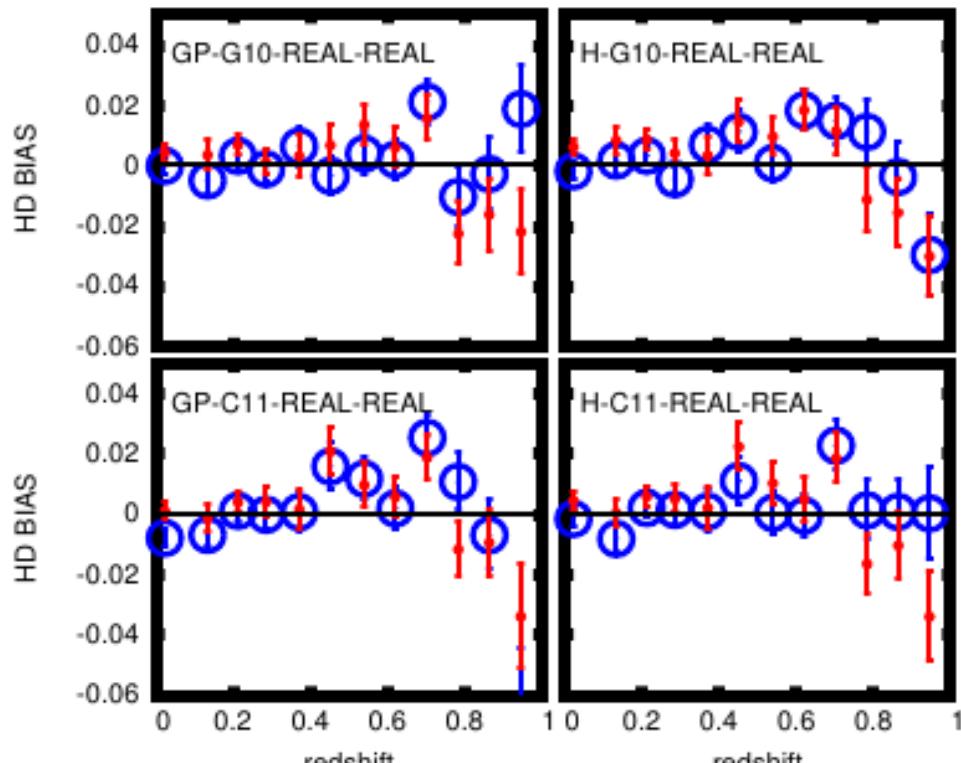
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SDSS/SNLS Joint Light Curves Analysis



- SNLS / SDSS JLA working group
 - Transverse WG to share data, code & expertise
 - Started in June 2010
 - Mainly focussed on systematics
- 4 papers
 - Calibration : Betoule & al, 2013
 - SNIa model systematics : Kessler et al, 2013, Mosher et al, 2014
 - Cosmology : Betoule et al, 2014

QUANTIFY SYSTEMATICS ASSOCIATED TO SALT2 MODEL



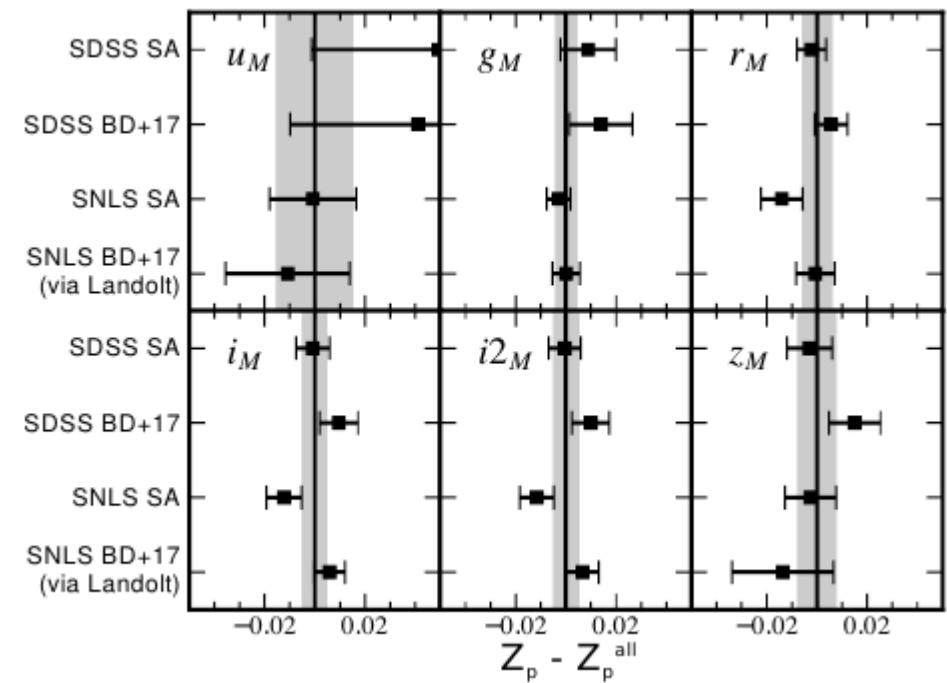
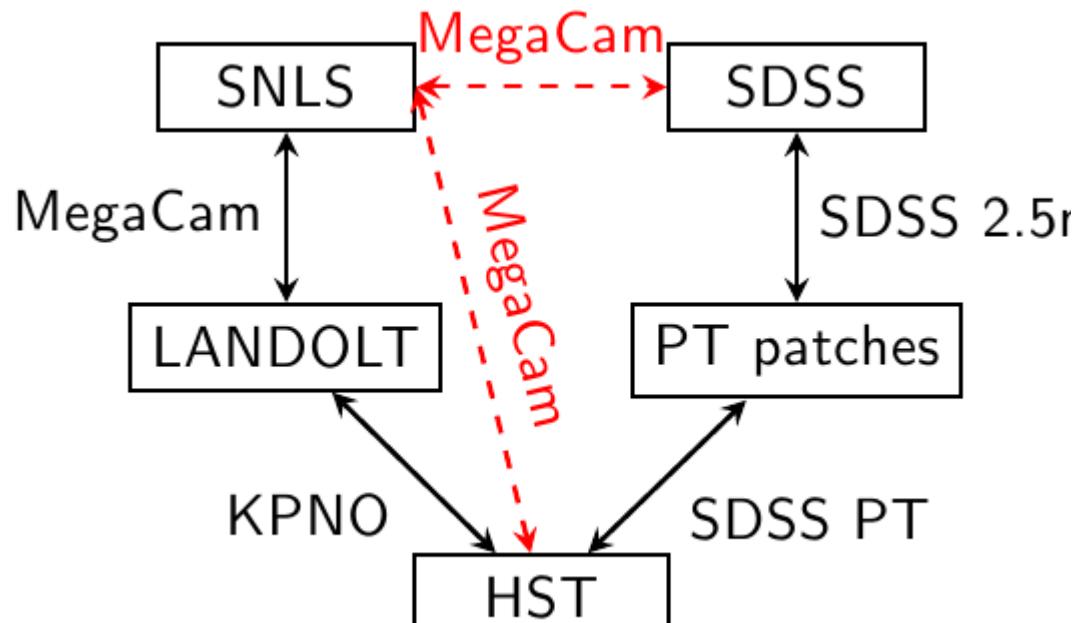
Mosher et al, 2014

- End to end test of SALT2
 - SN models as input
 - MC simulation
 - realistic training samples
 - training of SALT2
 - distances
 - Test the bias on reconstructed distances

$$\Delta\mu < 0.03$$

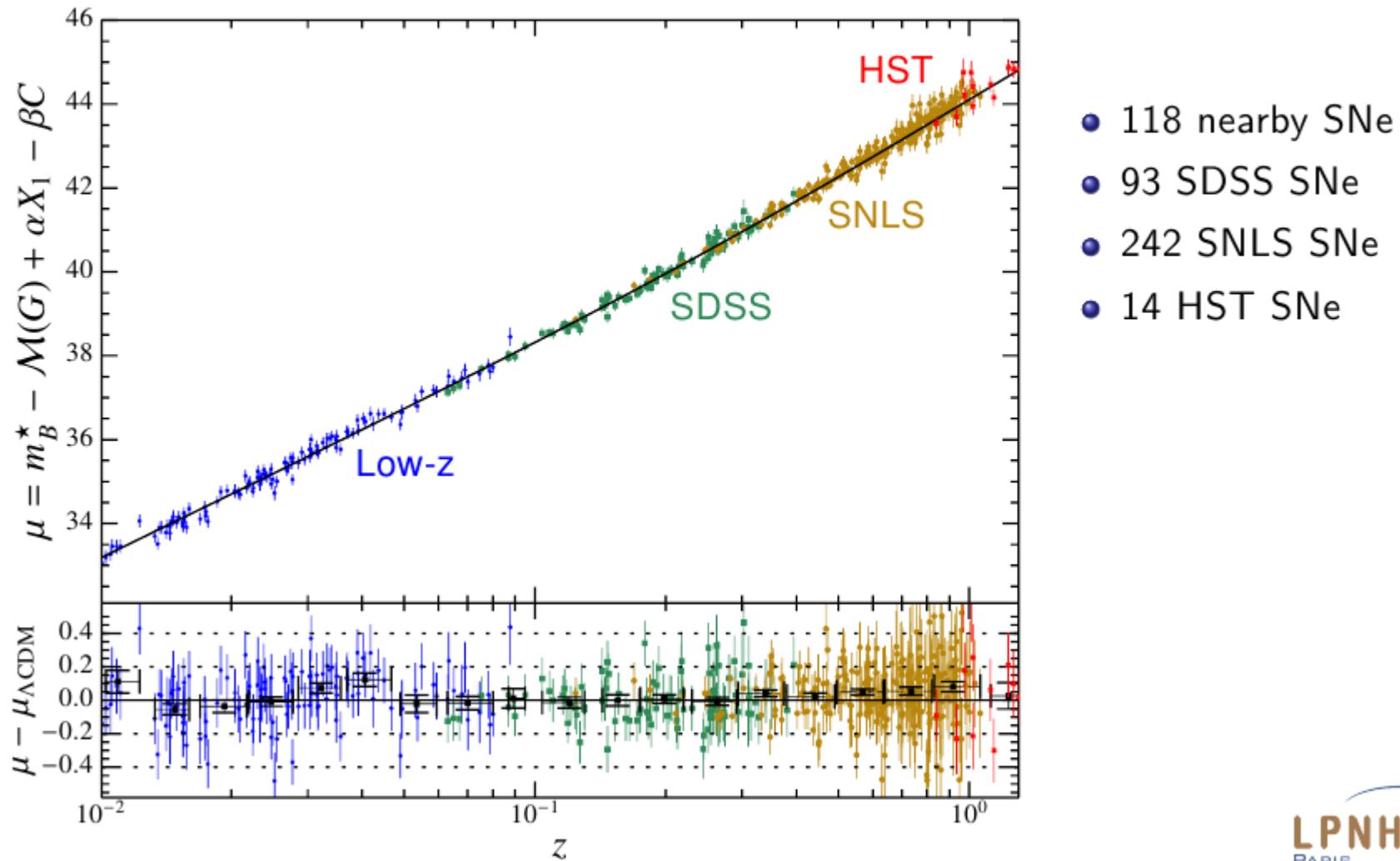
Well below current level of calibration uncertainties

JLA : CALIBRATION

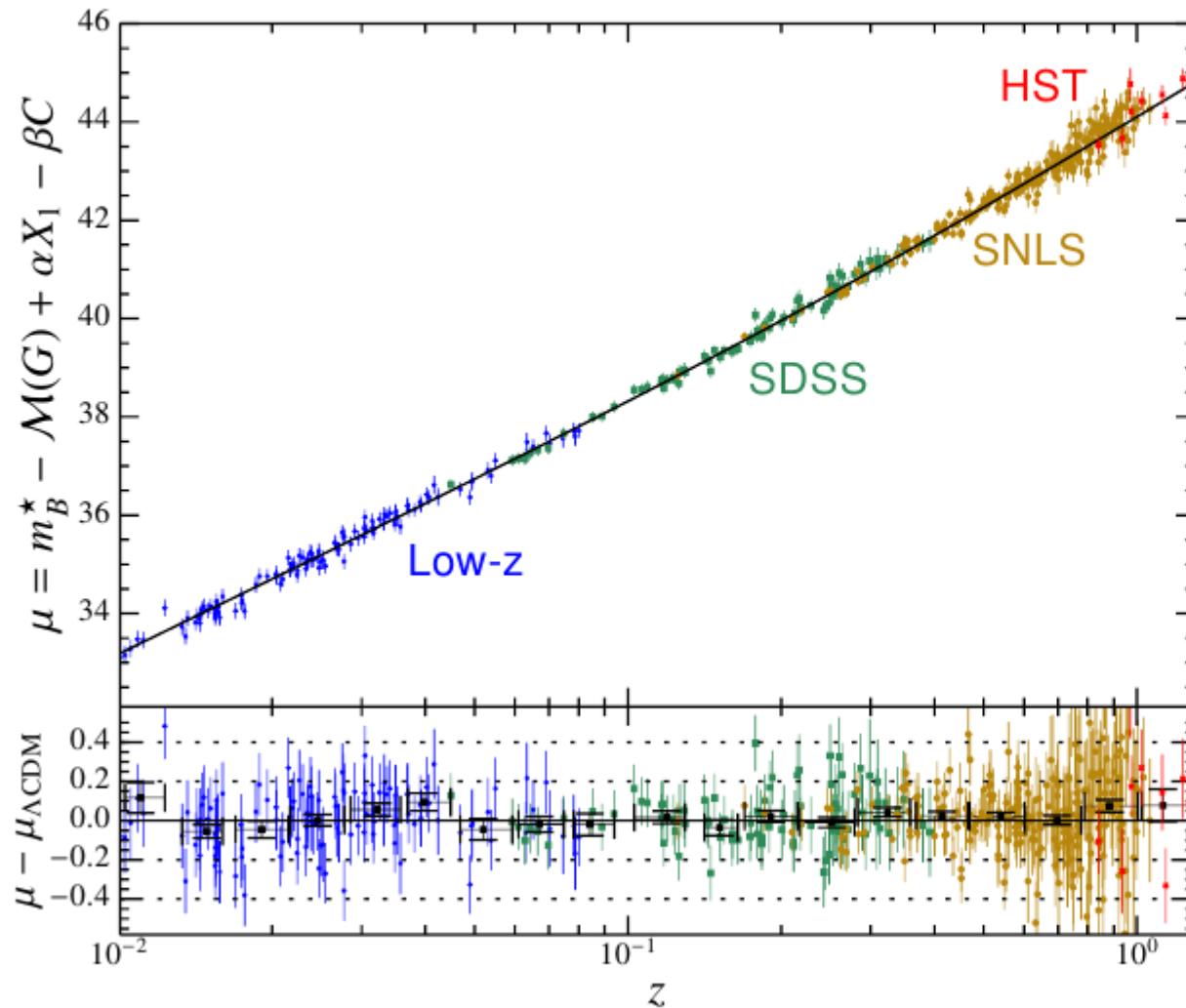


- Direct observations of SDSS & HST stars
- Several calibration paths
- 0.3% accuracy in gri

Start from the Conley et al. (2011) Salt2 Hubble diagram



Start from the Conley et al. (2011) Salt2 Hubble diagram

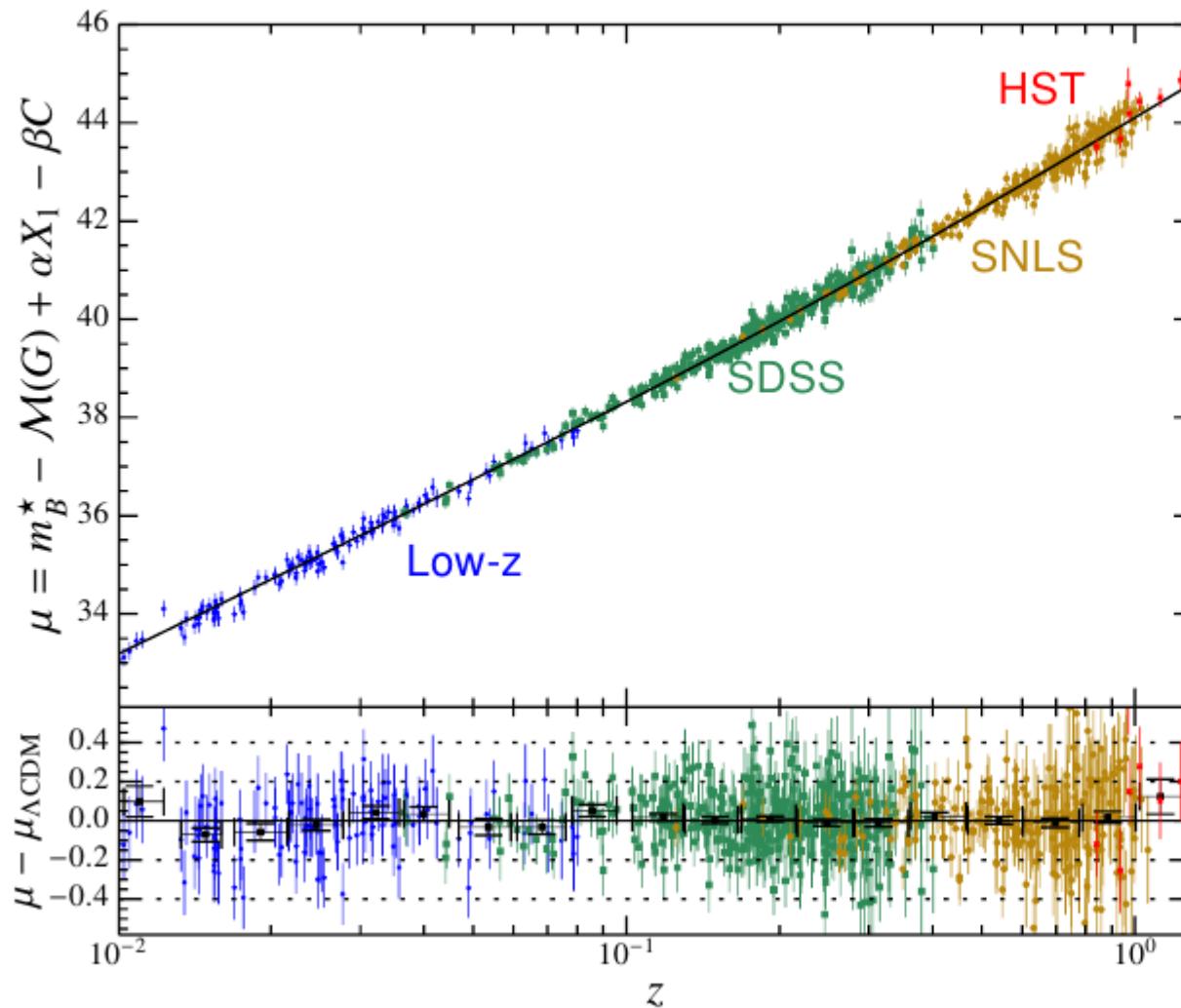


- 118 nearby SNe
- 93 SDSS SNe
- 242 SNLS SNe
- 14 HST SNe

Minimal update

- ➊ Recalibrate SNLS and SDSS

Start from the Conley et al. (2011) Salt2 Hubble diagram

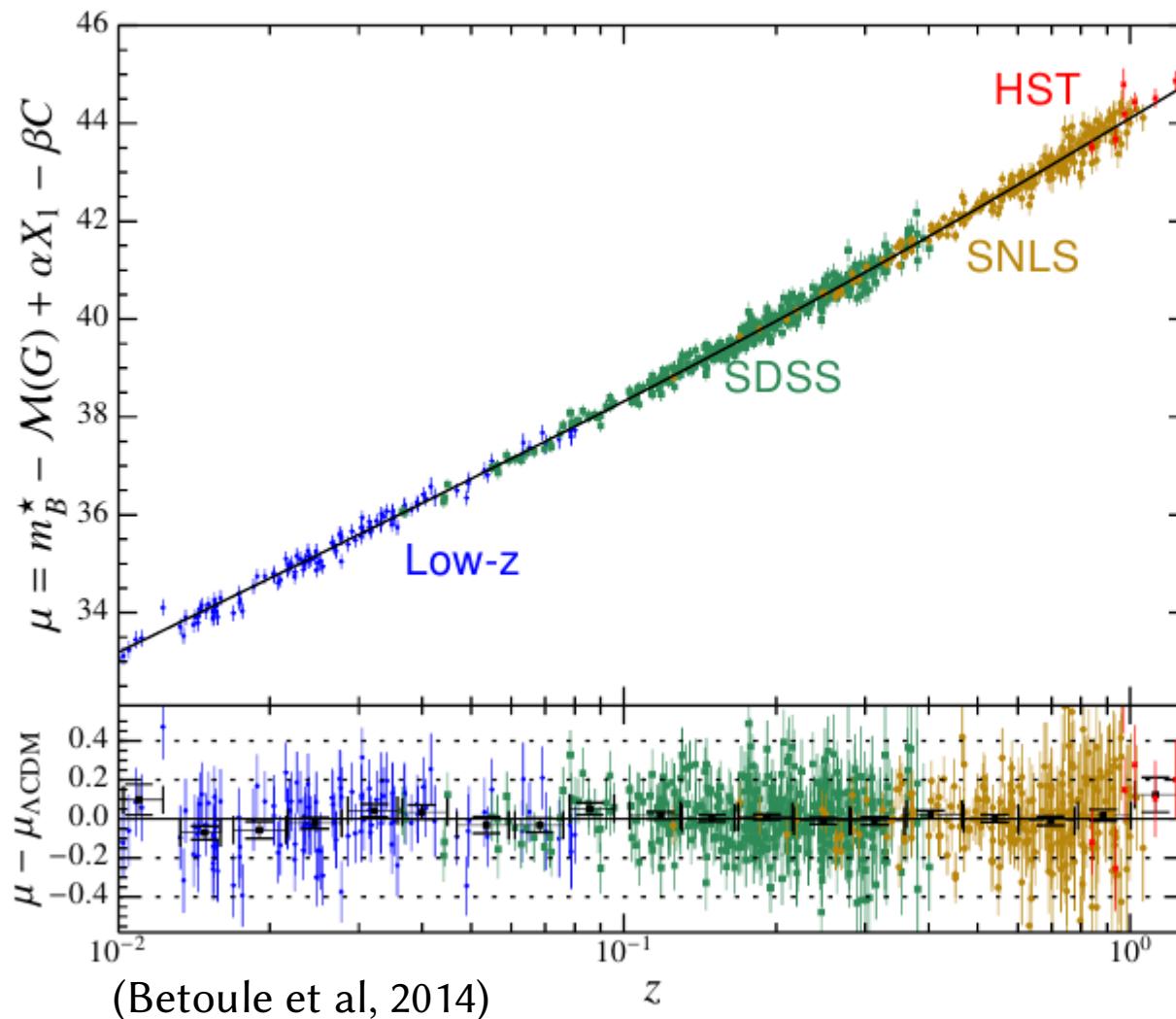


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- ➊ Recalibrate SNLS and SDSS
- ➋ Add ~ 270 SNe-Ia

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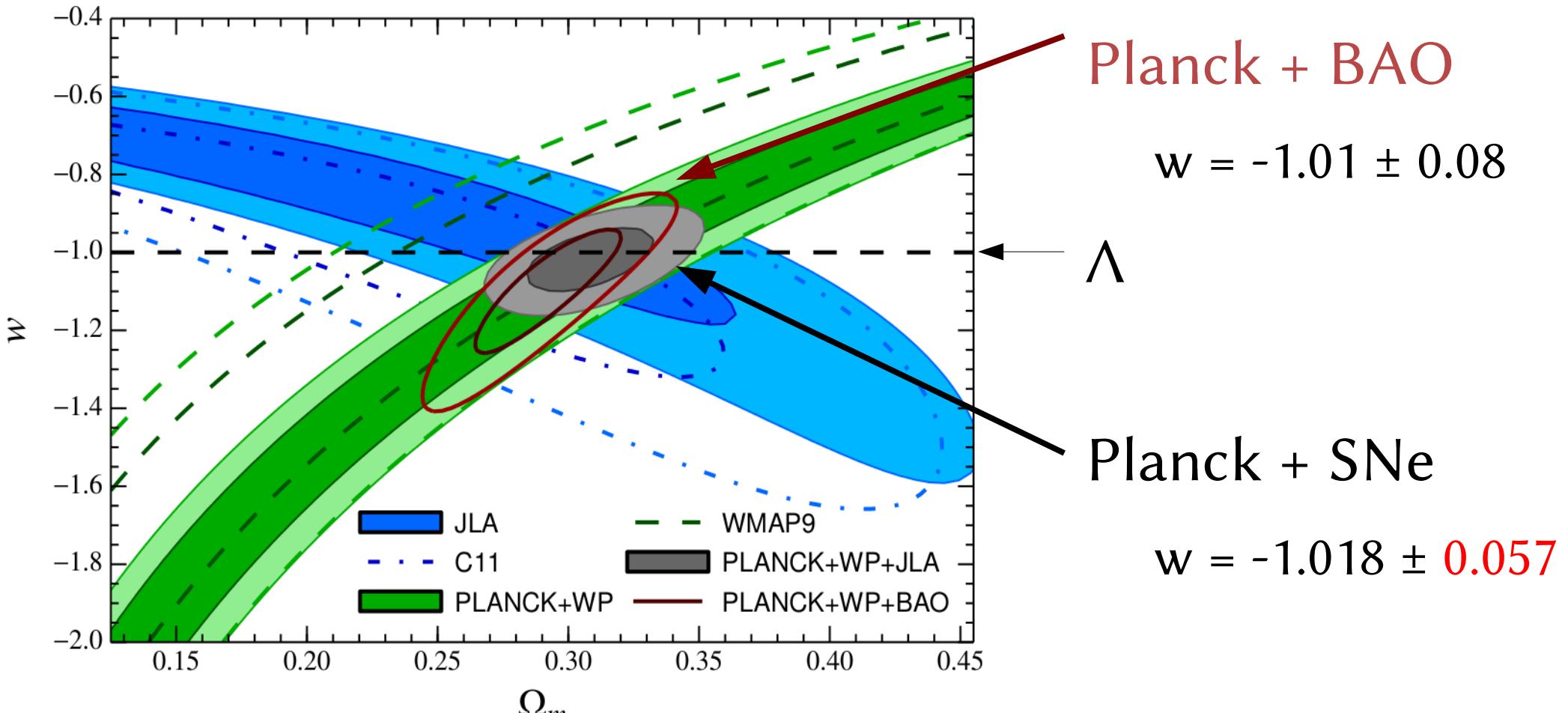
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JLA sample: 740 SNe
(Betoule et al. 2014)

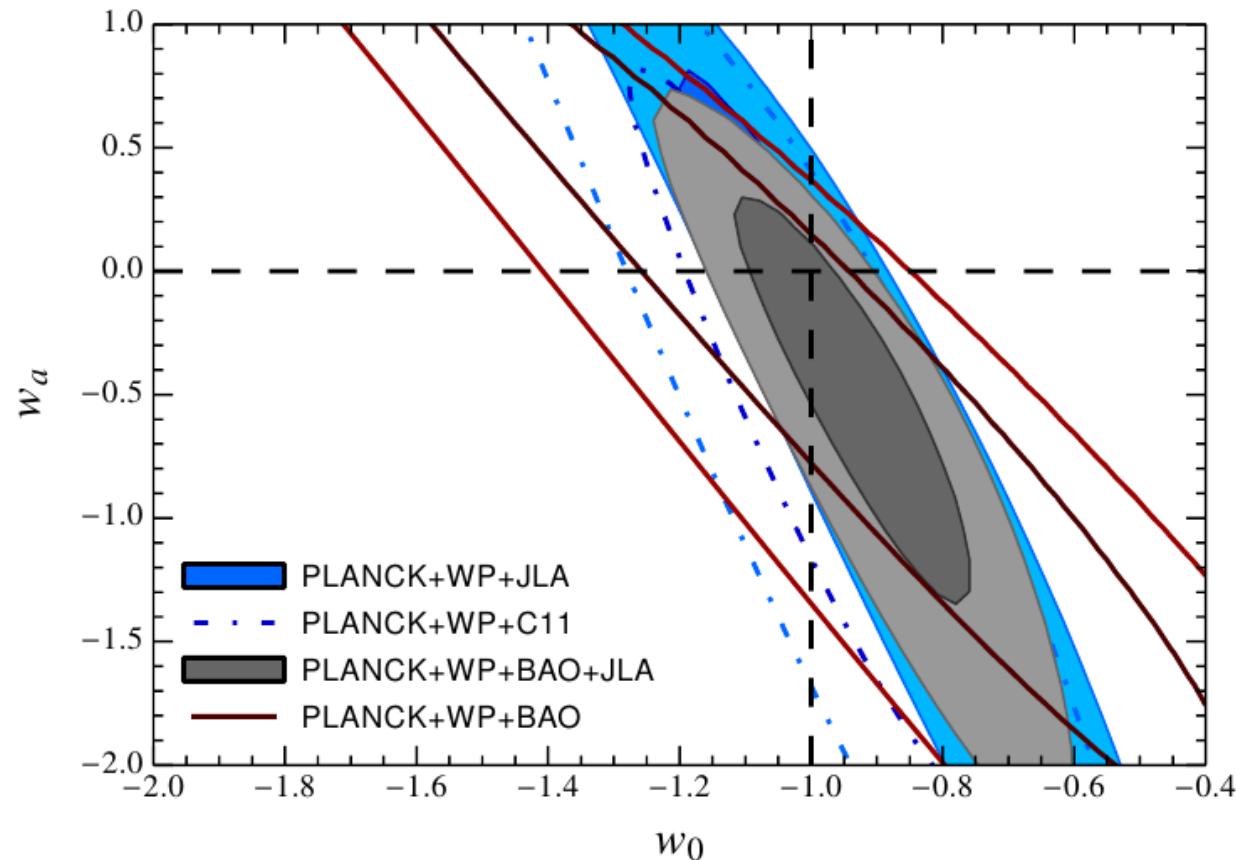
FLAT wCDM



(Betoule et al, 2014)

(see also Suzuki et al '12,
Rest et al '13, Scolnic et al '13...)

w_0 , w_a



DETF FoM ~ 30

Ingredients

- Large SDSS dataset
- Calibration accuracy
- Better CMB + BAO

DETF : Albrecht et al '06

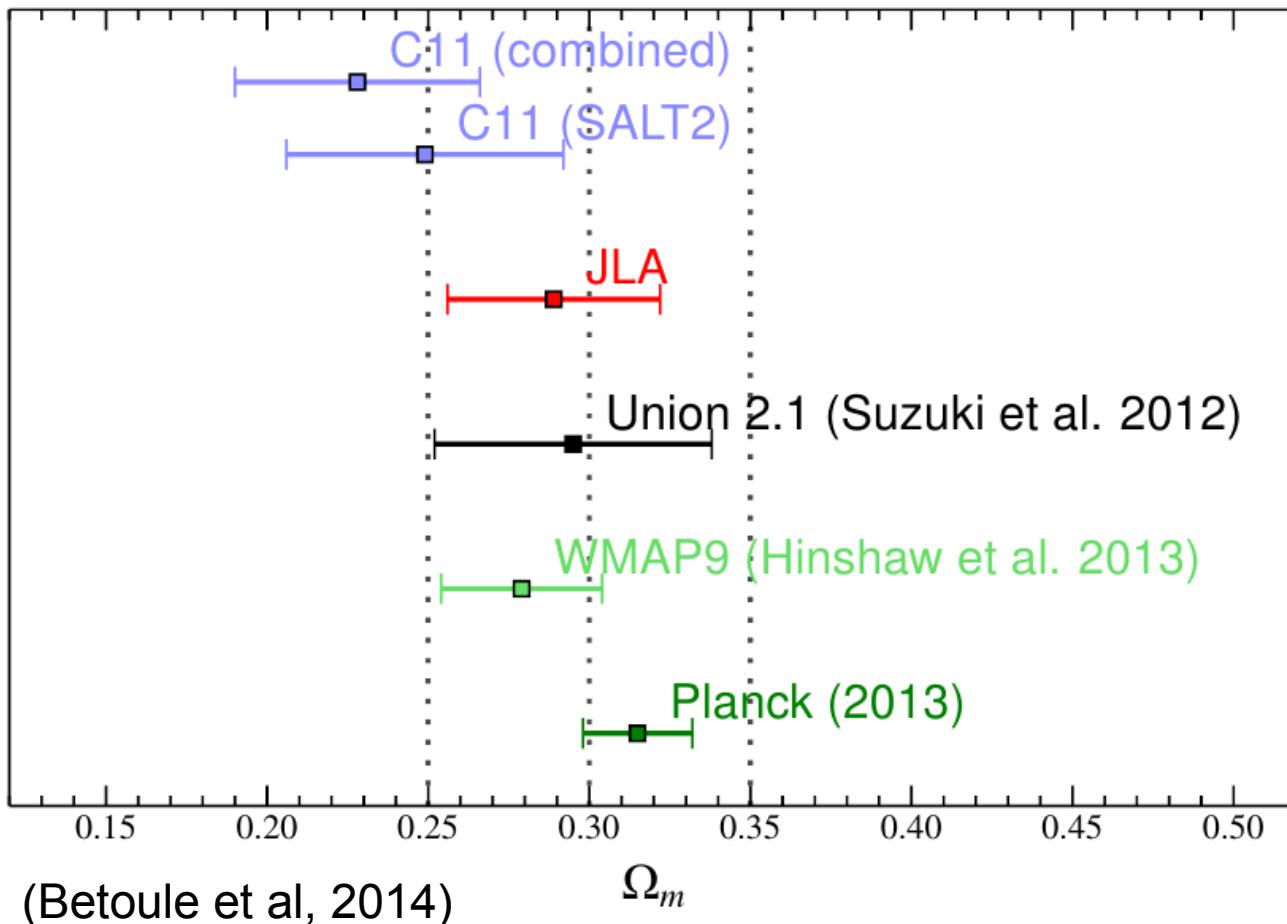
See also: Peacock et al '06

Is JLA COMPATIBLE WITH Λ CDM ?

Planck 2013 results. XVI. Cosmological parameters

Abstract: This paper presents the first cosmological results based on *Planck* measurements of the cosmic microwave background (CMB) temperature and lensing-potential power spectra. We find that the *Planck* spectra at high multipoles ($\ell \gtrsim 40$) are extremely well described by the standard spatially-flat six-parameter Λ CDM cosmology with a power-law spectrum of adiabatic scalar perturbations. Within the context of this cosmology, the *Planck* data determine the cosmological parameters to high precision: the angular size of the sound horizon at recombination, the physical densities of baryons and cold dark matter, and the scalar spectral index are estimated to be $\theta_* = (1.04147 \pm 0.00062) \times 10^{-2}$, $\Omega_b h^2 = 0.02205 \pm 0.00028$, $\Omega_c h^2 = 0.1199 \pm 0.0027$, and $n_s = 0.9603 \pm 0.0073$, respectively (68% errors). For this cosmology, we find a low value of the Hubble constant, $H_0 = 67.3 \pm 1.2 \text{ km s}^{-1} \text{ Mpc}^{-1}$, and a high value of the matter density parameter, $\Omega_m = 0.315 \pm 0.017$. These values are in tension with recent direct measurements of H_0 and the magnitude-redshift relation for Type Ia supernovae, but are in excellent agreement with geometrical constraints from baryon acoustic oscillation (BAO) surveys. Including curvature, we find that the Universe is consistent with spatial flatness to percent level precision using *Planck* CMB data alone. We use high-resolution CMB data together with *Planck* to provide greater control on extragalactic foreground components in an investigation of extensions to the six-parameter Λ CDM model. We present selected results from a large grid of cosmological models, using a range of additional astrophysical data sets in addition to *Planck* and high-resolution CMB data. None of these models are favoured over the standard six-parameter Λ CDM cosmology. The deviation of the scalar spectral index from unity is insensitive to the addition of tensor modes and to changes in the matter content of the Universe. We find a 95% upper limit of $r_{0.002} < 0.11$ on the tensor-to-scalar ratio. There is no evidence for additional neutrino-like relativistic particles beyond the three families of neutrinos in the standard model. Using BAO and CMB data, we find $N_{\text{eff}} = 3.30 \pm 0.27$ for the effective number of relativistic degrees of freedom, and an upper limit of 0.23 eV for the sum of neutrino masses. Our results are in excellent agreement with big bang nucleosynthesis and the standard value of $N_{\text{eff}} = 3.046$. We find no evidence for dynamical dark energy; using BAO and CMB data, the dark energy equation of state parameter is constrained to be $w = -1.13^{+0.13}_{-0.10}$. We also use the *Planck* data to set limits on a possible variation of the fine-structure constant, dark matter annihilation and primordial magnetic fields. Despite the success of the six-parameter Λ CDM model in describing the *Planck* data at high multipoles, we note that this cosmology does not provide a good fit to the temperature power spectrum at low multipoles. The unusual shape of the spectrum in the multipole range $20 \lesssim \ell \lesssim 40$ was seen previously in the *WMAP* data and is a real feature of the primordial CMB anisotropies. The poor fit to the spectrum at low multipoles is not of decisive significance, but is an “anomaly” in an otherwise self-consistent analysis of the *Planck* temperature data.

FLAT Λ CDM



- Ω_m measurement independent of CMB and compatible with Planck.

Changes vs. SNLS3 driven by recalibration
(+ LC fitters)

ABOUT H_0

- High-z SN surveys measure **relative distances**

$$\frac{\ell(z)}{\mathcal{L}_0} = \propto \frac{1}{d_L^2(z)}$$

with

$$d_L(z) = (1+z) \frac{c}{H_0} \int dz' \left(\Omega_m (1+z)^2 + \Omega_X (1+z)^{3(1+w)} \right)^{-1/2}$$

$\mathcal{L}_0 H_0^2$ is in fact a *nuisance parameter* !

- Measuring H_0 requires
 - Absolute measurements of distances
 - (see e.g. Riess et al, 2011)

SYSTEMATICS

Uncertainty sources	$\sigma_x(\Omega_m)$	% of $\sigma^2(\Omega_m)$
Calibration	0.0203	36.7
Milky Way extinction	0.0072	4.6
Light-curve model	0.0069	4.3
Bias corrections	0.0040	1.4
Host relation ^a	0.0038	1.3
Contamination	0.0008	0.1
Peculiar velocity	0.0007	0.0
Stat	0.0241	51.6

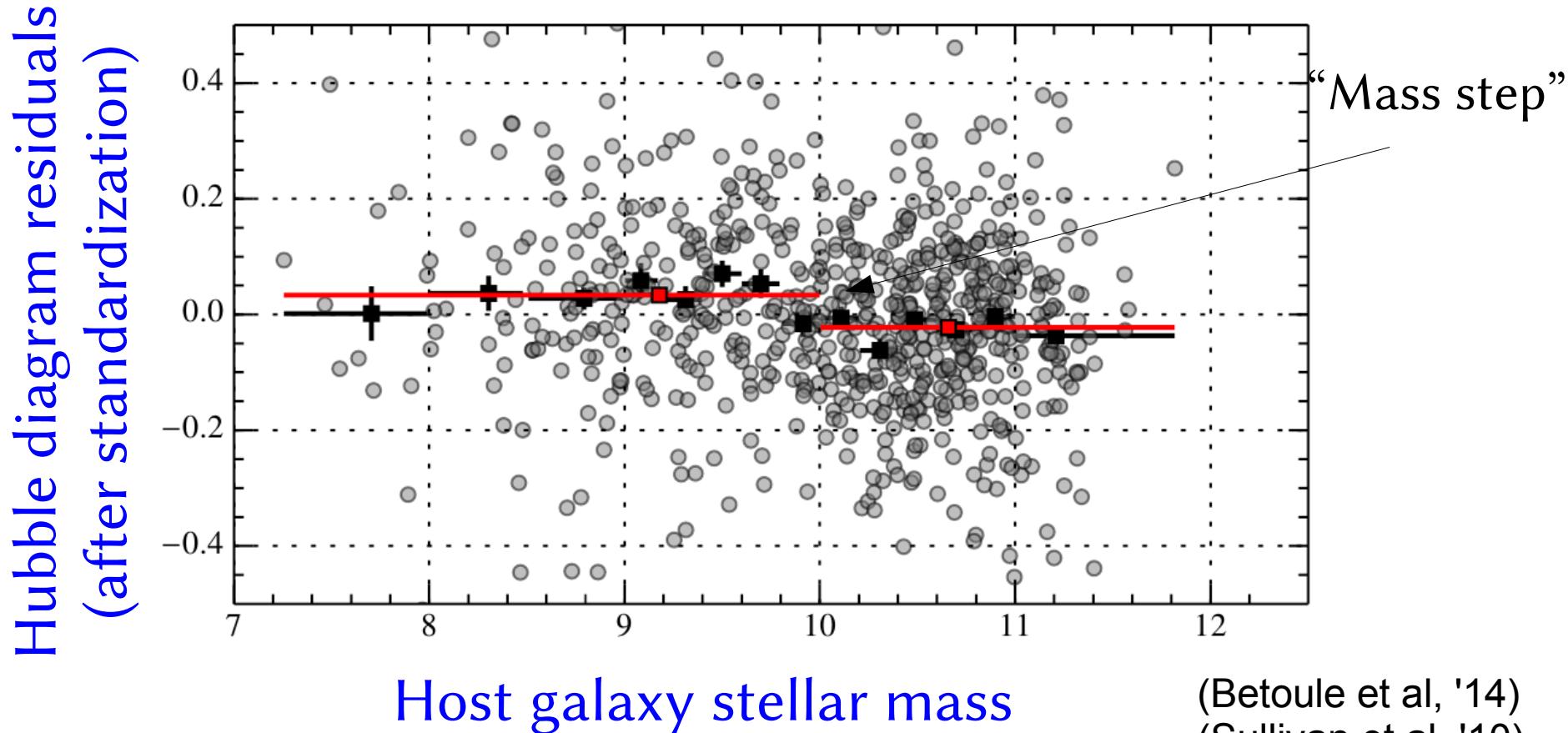
(Betoule et al, 2014)

Photometric calibration (still) dominates
the systematic uncertainty budget.

EVOLUTION

- Universe today different from Universe @ $z \sim 1$
 - e.g. 8 times less star formation
 - Mix old, evolved elliptical gals / young, star forming gals has changed
- SN Ia properties sensitive to their environment
 - 10 times more SNIa in star forming gals (Mannuci'05, Sullivan'06)
→ 2 populations ?
 - SN in active galaxies brighter than SNe in passive galaxies (Hamuy'96, Howell'07)
- However
 - Howell'07: is accounted for by standardization relations
 - No syst. spectroscopic differences between low-z & hi-z

ASTROPHYSICAL SYSTEMATICS



- **Astrophysical systematics**

- 2 populations + evolving demographics ?
- Absorbed into 1 additional parameter

BUT: Barely detectable in Pan-STARRS, e.g. (Scolnic '13)

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MORE SUPERNOVAE

- On going surveys

- CfA, CSP $z < 0.1$
- PTF (Law et al, 2009) $z < 0.1$
- SN factory (Aldering 2002) $z < 0.1$
- Pan STARRS (Scolnic '14) $z < 0.7$

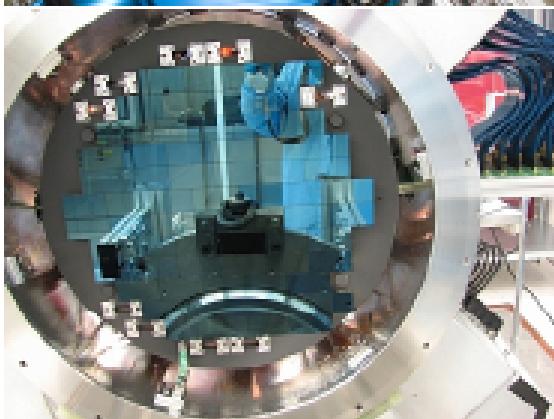
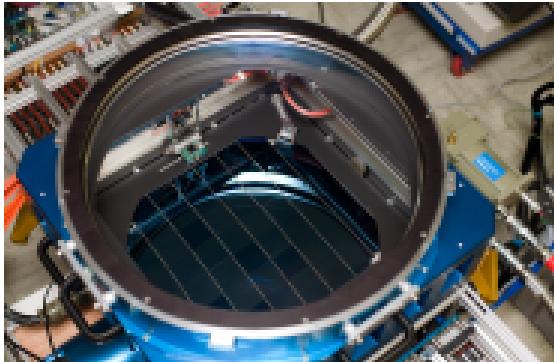
- Starting now

- DES (Bernstein, 2011) $z < 1.2$
- SkyMapper $z \sim 0.1$

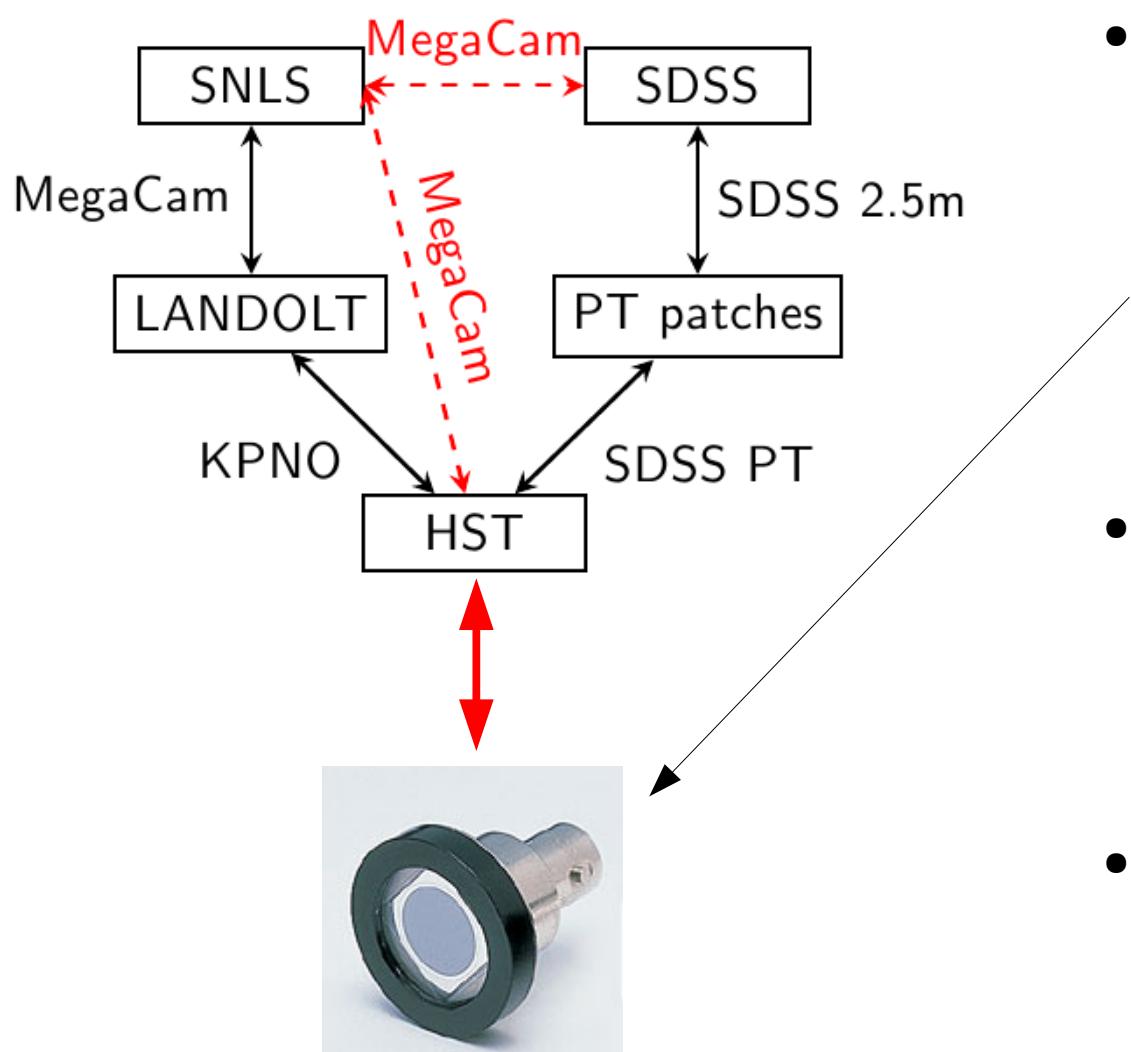
- ...

- 2020 +

- LSST, EUCLID $0.1 < z < 1.5$



INSTRUMENTAL CALIBRATION



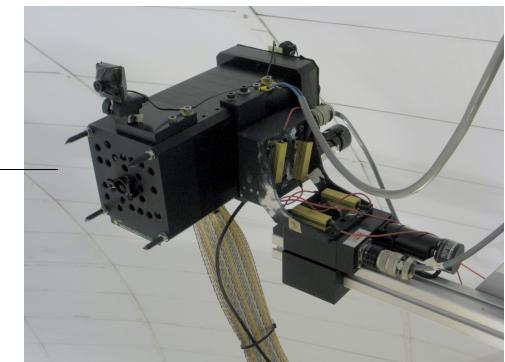
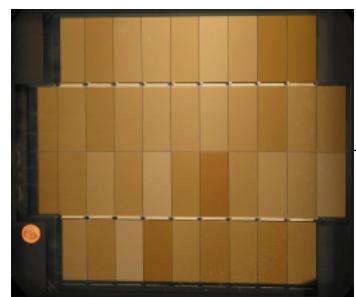
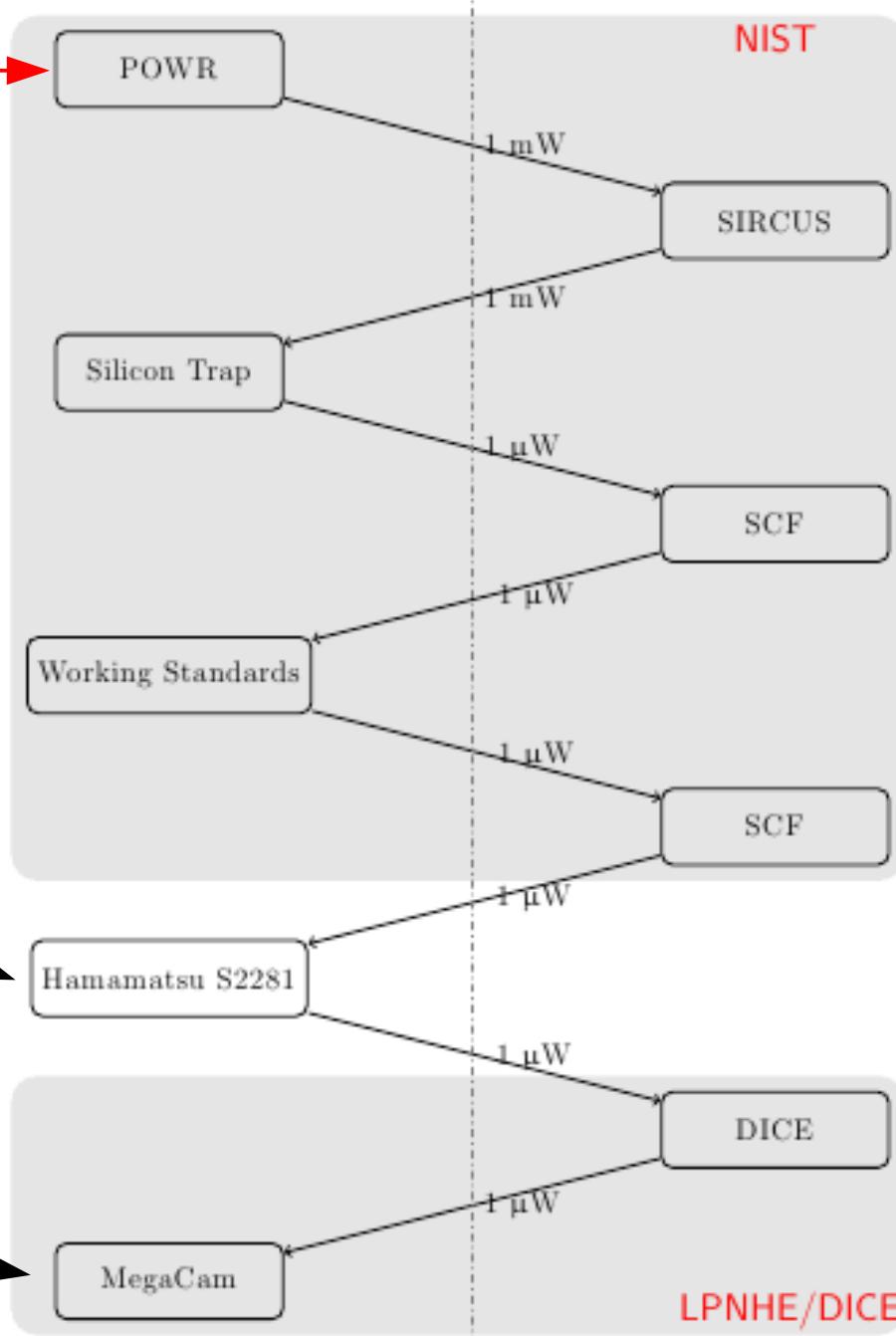
- Stellar flux standards
vs
Laboratory standards
- Precision monitoring of large focal planes
- 0.1% calibration accuracy

Hamamatsu S2281

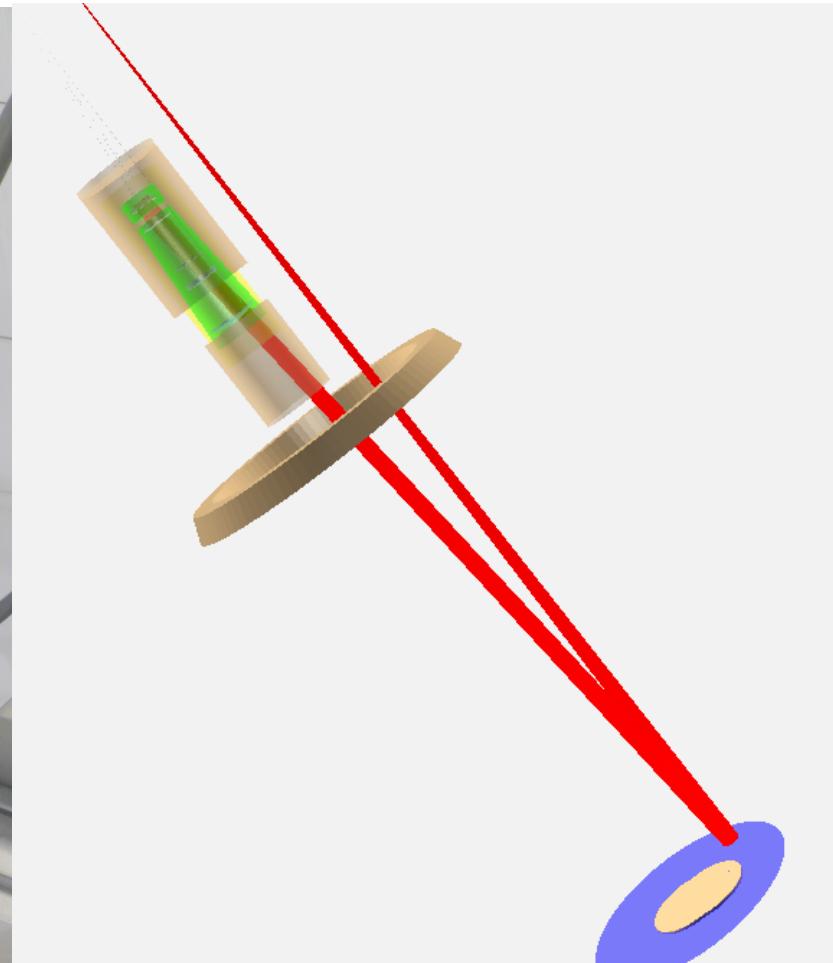
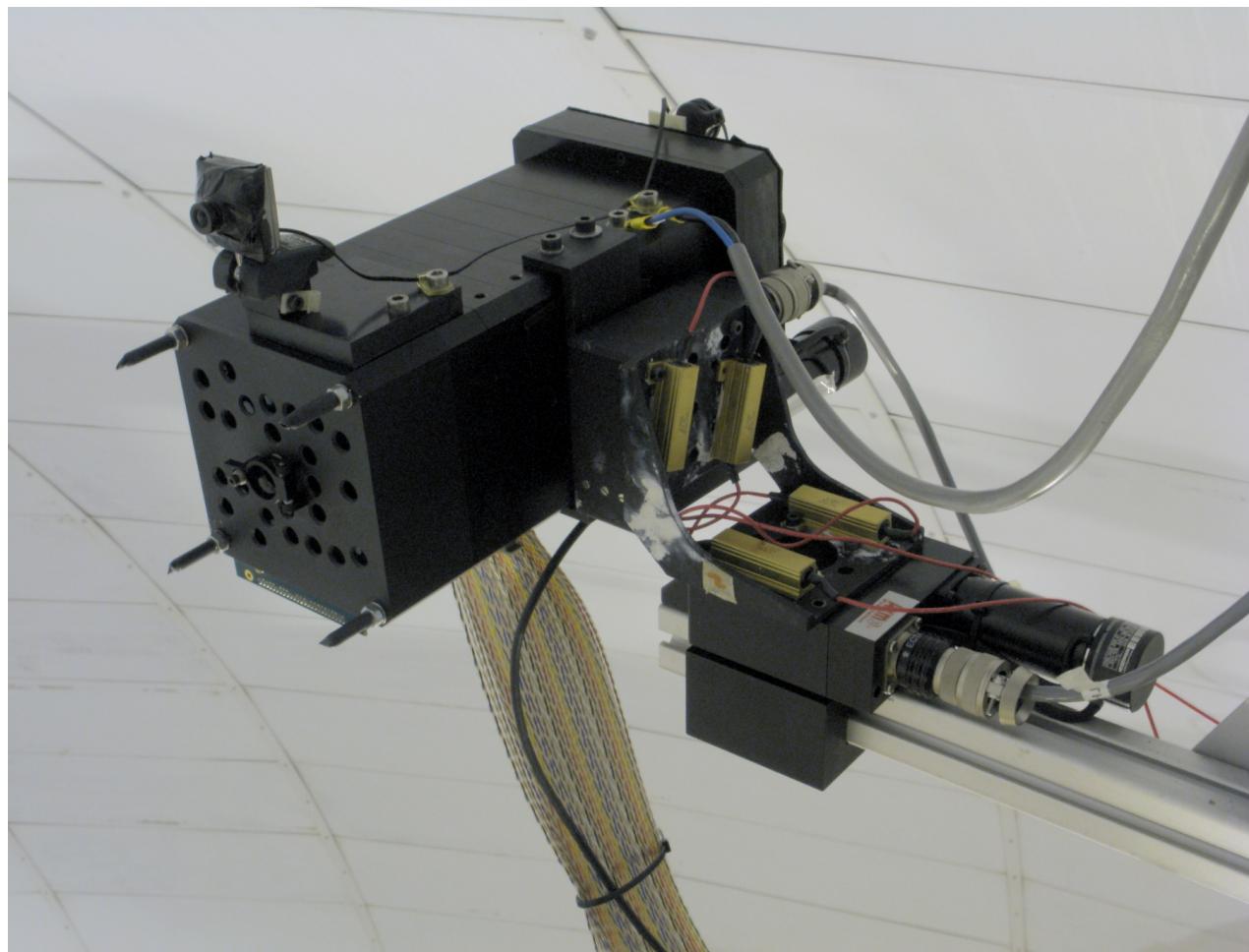


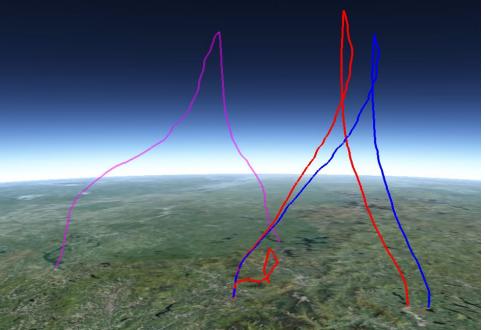
DETECTORS

SOURCES



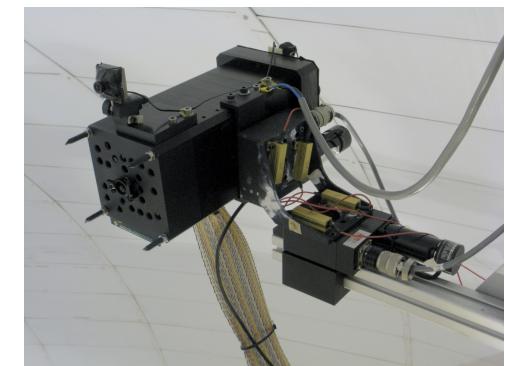
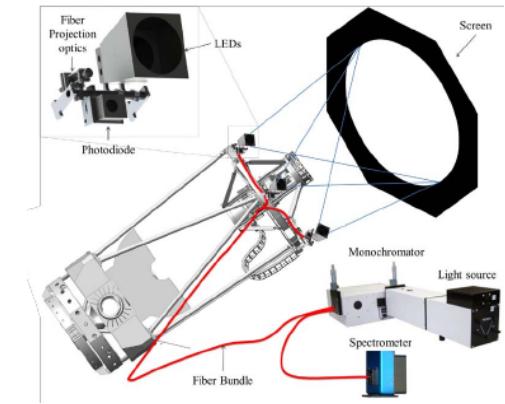
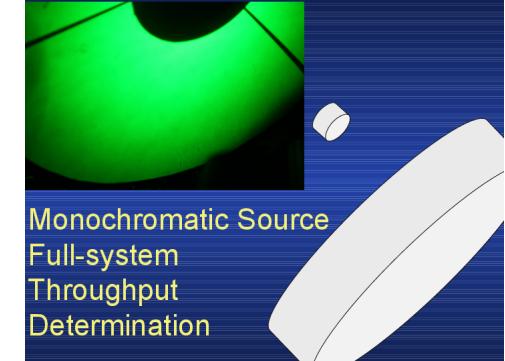
INSTRUMENTAL CALIBRATION



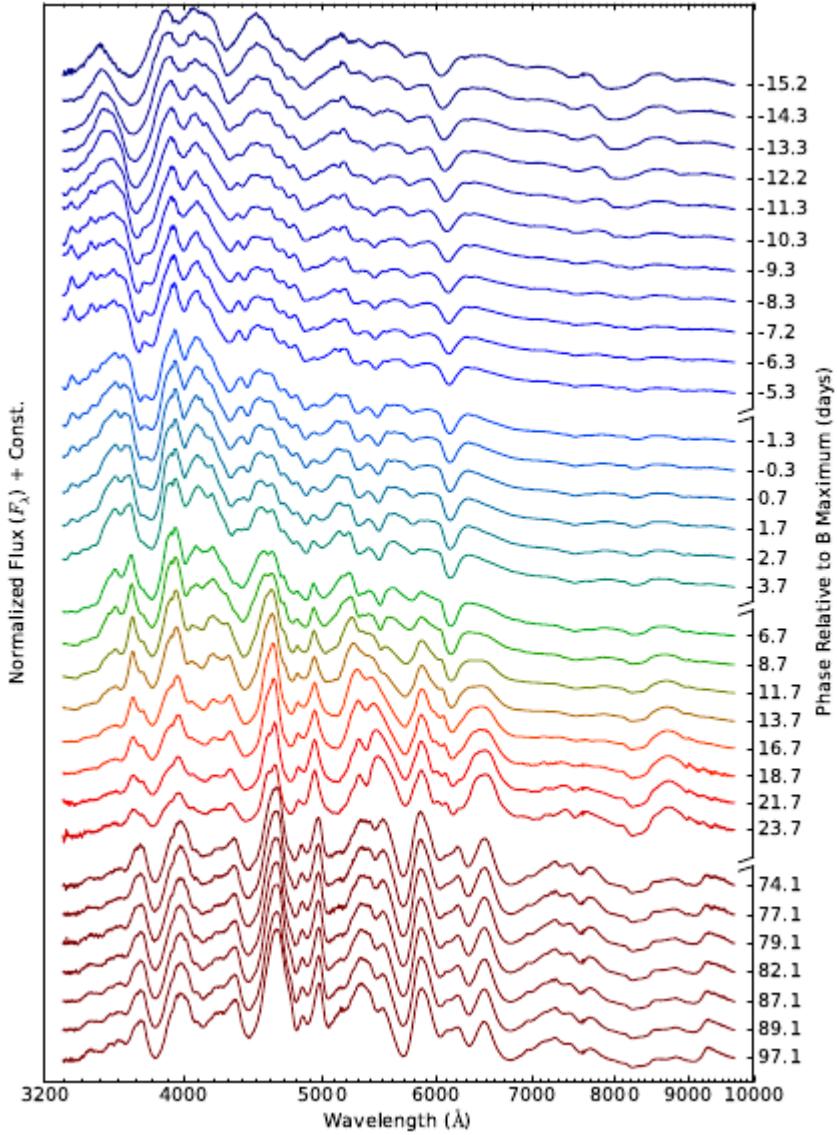


CALIBRATION PROJECTS

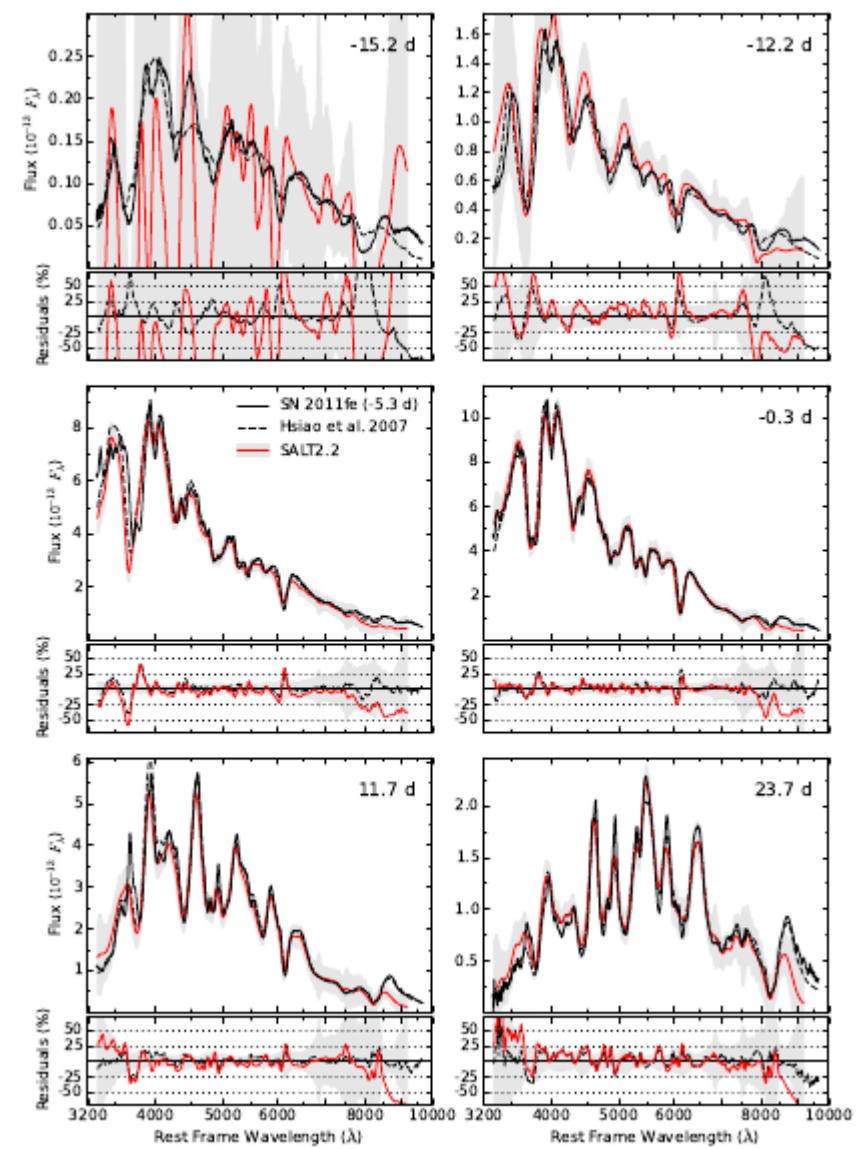
- Harvard (Stubbs et al)
 - ESSENCE
 - PanSTARRS
- Texas A&M (DePoy et al)
 - DES (Dark Energy Survey)
- NIST (Cramer et al)
 - Artificial star → recalibration of Vega
- LPNHE
 - SnDICE (MegaCam)
 - SkyDICE (SkyMapper)



IMPROVING SN MODELS WITH NEW DATA

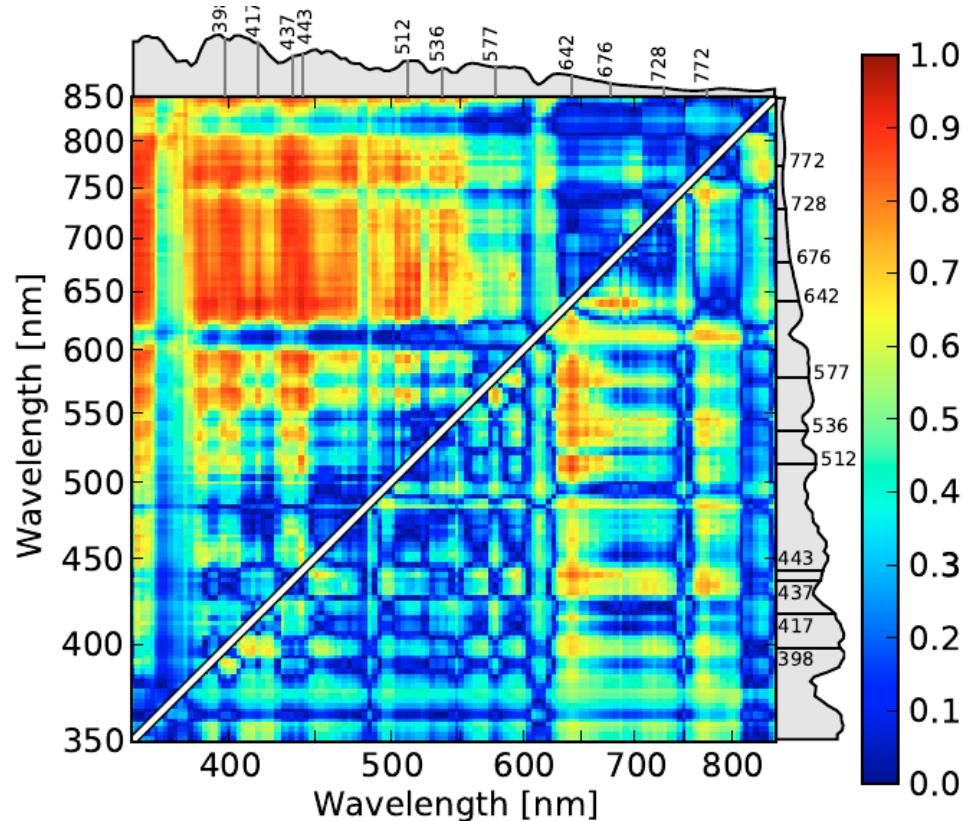


Time evolution of SN 2011fe



Comparison w/ SALT2

BETTER SN STANDARDIZATION ?



- Spectroscopic standardization
 - Systematic search (Bailey et al '09)
 - $\sigma(M) \sim 0.12$
- Not competitive with photometry based techniques
(at least for hi-z SNe)
- New observables ?
 - Galaxy colors ?
 - SN color evolution ?
 - LC early parts ?

ORIGIN OF THE MASS STEP

- Physical explanation
 - Different progenitors ?
 - Progenitor metallicity ? (D'Andrea et al, '13, Pan et al'13)
 - Local instellar medium ? (Rigault et al'13, Childress et al, '13)
- Looking for counterparts in SN observables
 - Spectra ?
 - Early / late parts of light curves ?
 - ...

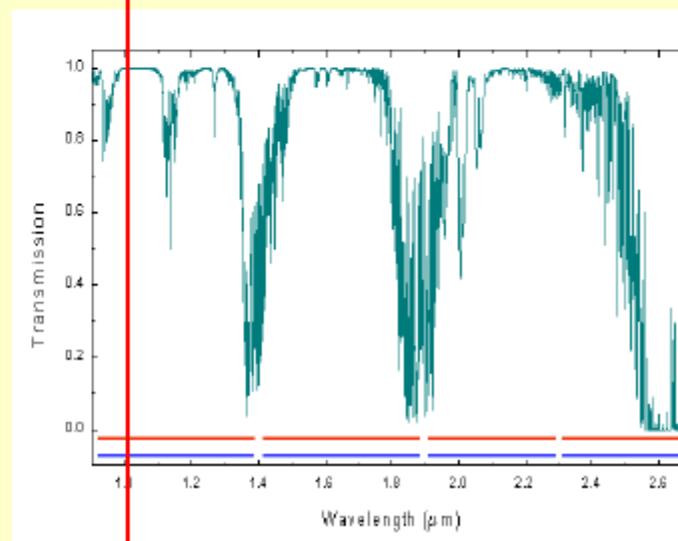
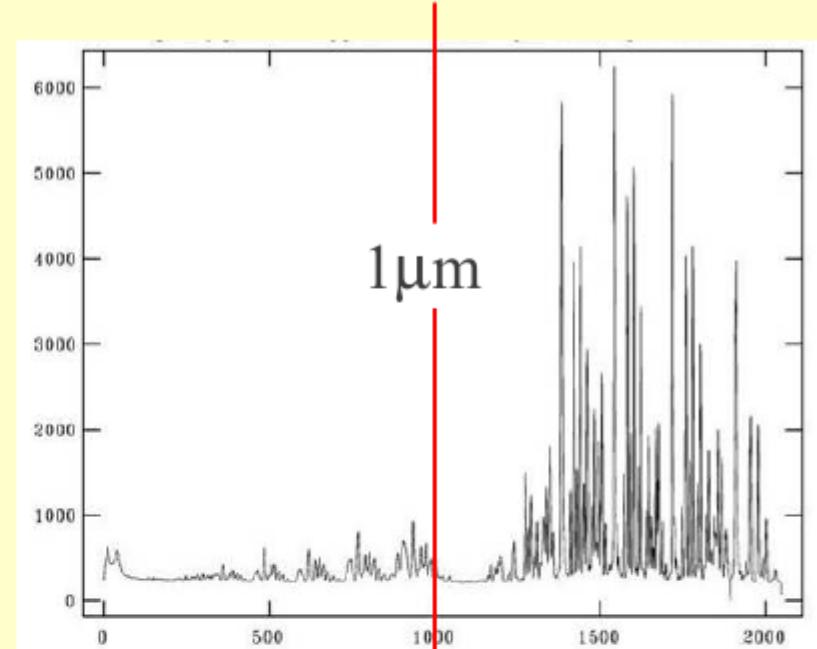
$z > 1$? GO TO SPACE !

There
Is
No

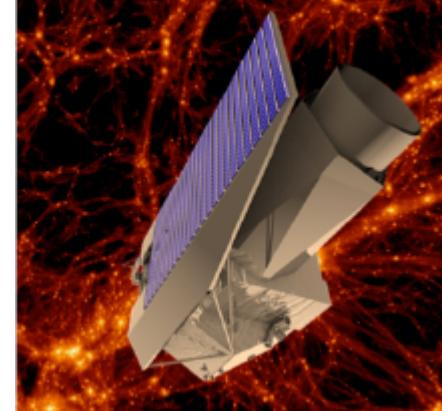
Atmospheric
emission

Alternative

Atmospheric
Absorption



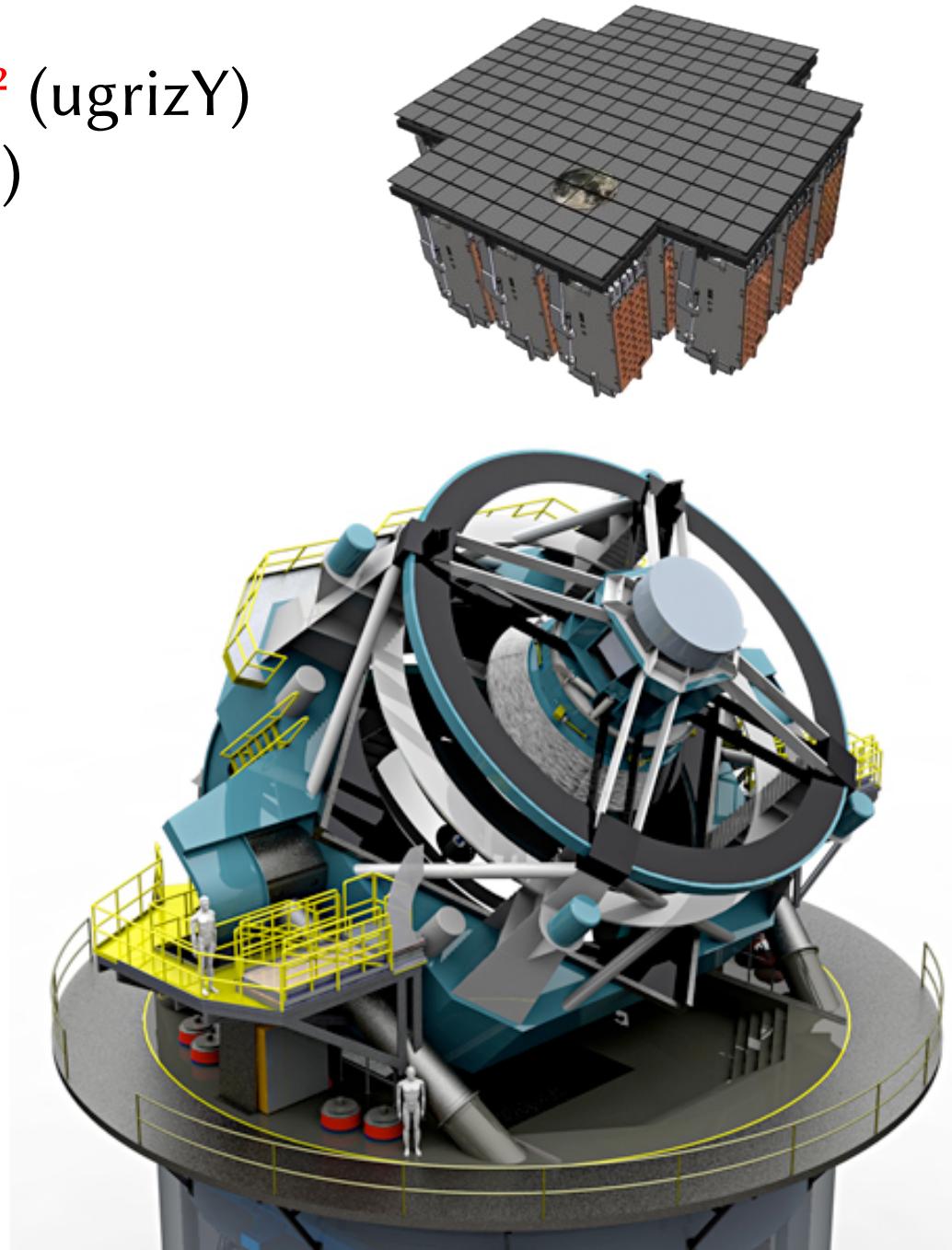
EUCLID



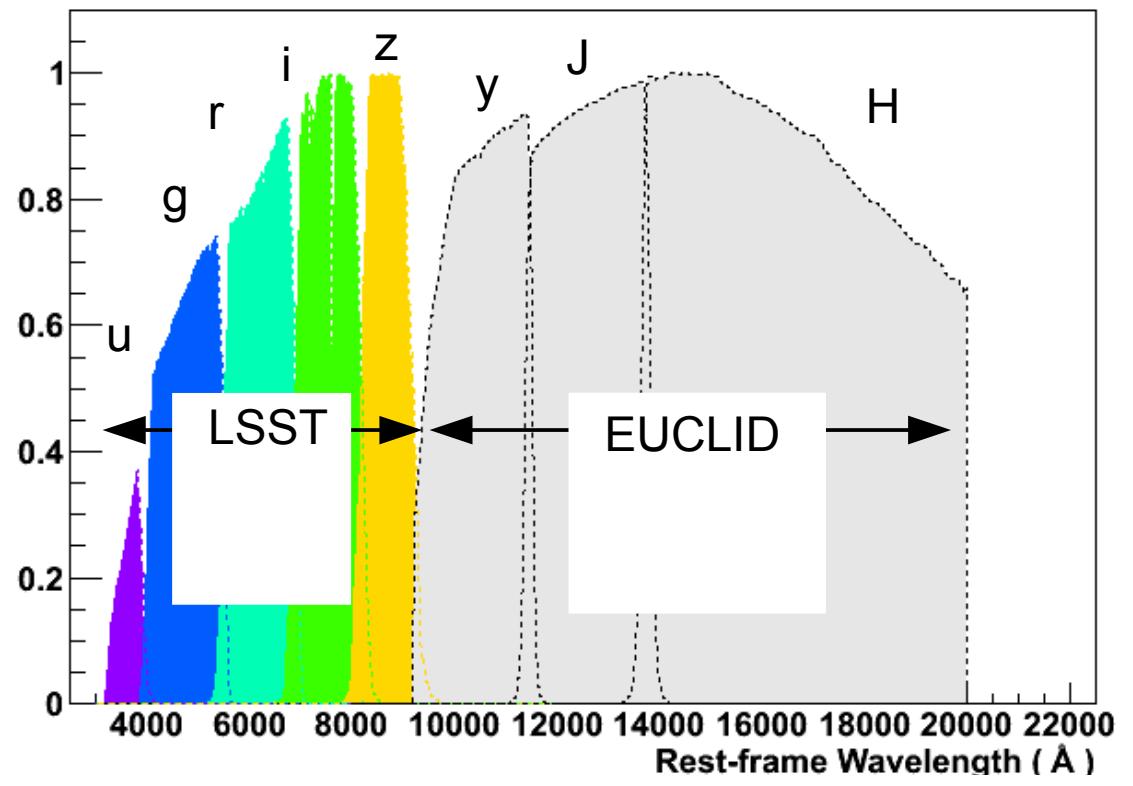
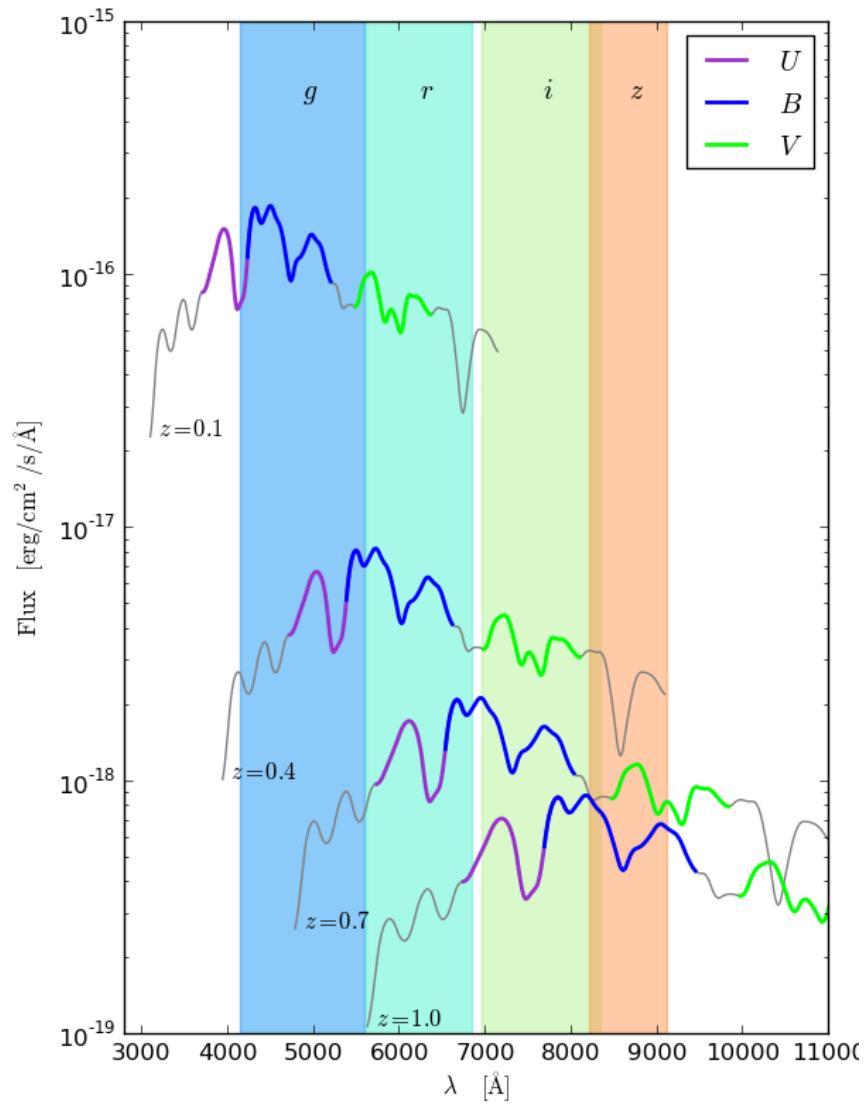
- ESA “M” mission (109 labs, 13 countries)
- 1.2-m - 0.5 deg² in the visible (1 band)
- 0.5 deg² in the infrared (3 bands)
- 15,000 deg²
- Lensing + BAO + (if possible) supernovae (IR)
- Group involvement :
 - SN science working group
 - SN survey design (exploring combining LSST + Euclid surveys)

LSST

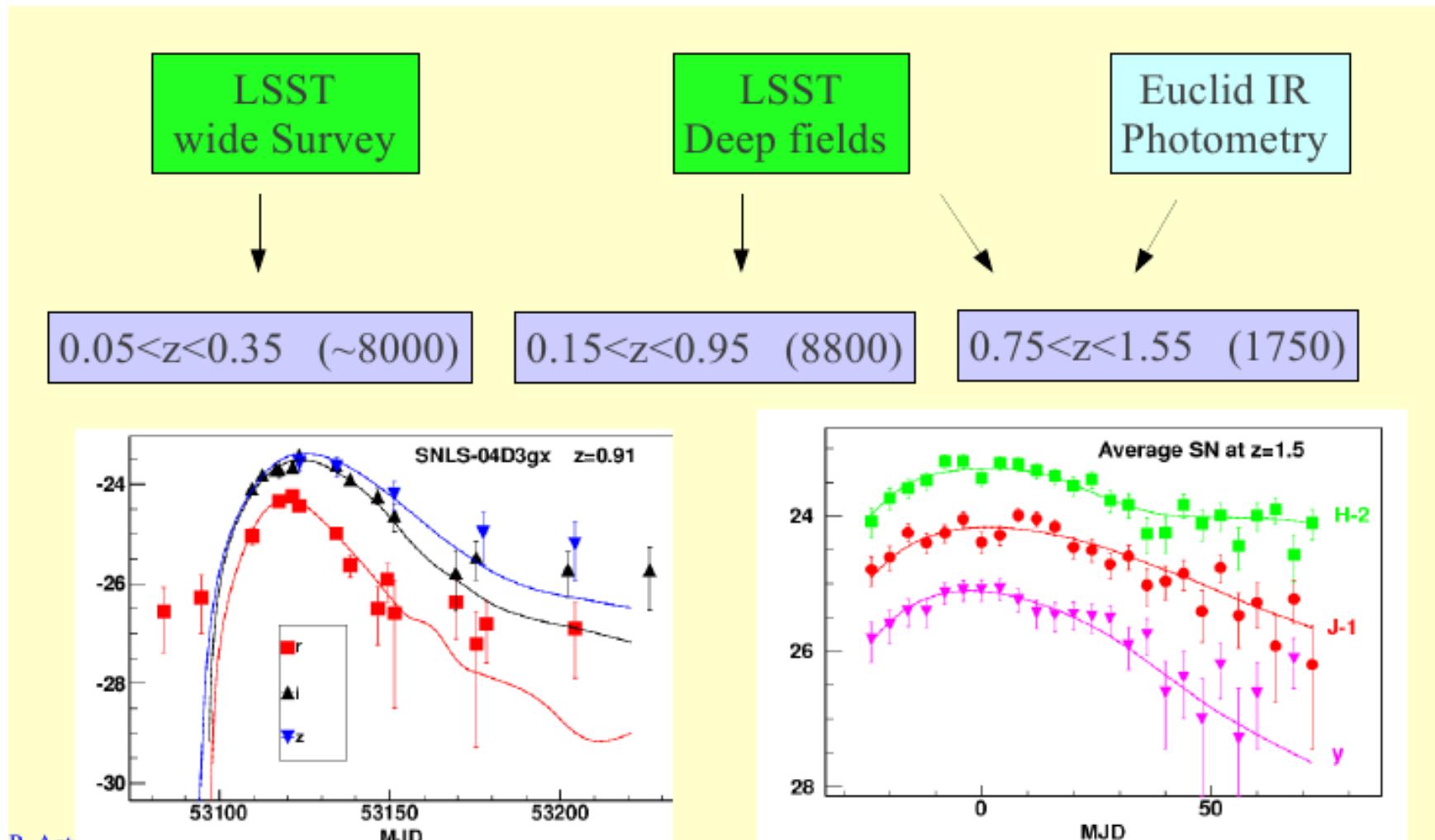
- 8.4 m (6-m equivalent), **9.6 deg²** (ugrizY)
- 3 Gigapixels, Fast readout ($\sim 2s$)
- All sky survey (20,000 deg²)
- + dedicated surveys
(e.g. Deep Drilling Fields)
- **Science**
 - Lensing
 - BAO (photometric redshifts)
 - Supernovae @ low & high z
 - Galactic structure
 - transients
 - ...



EUCLID + LSST



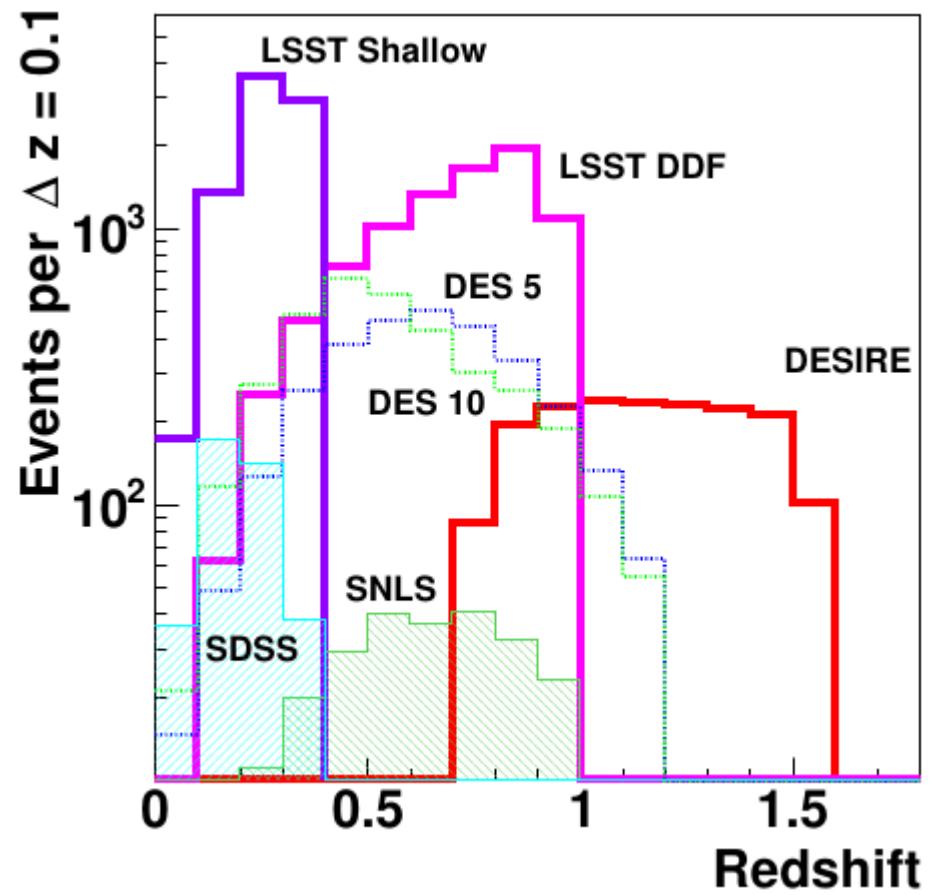
Euclid + LSST



LSST + EUCLID : DISCOVERIES

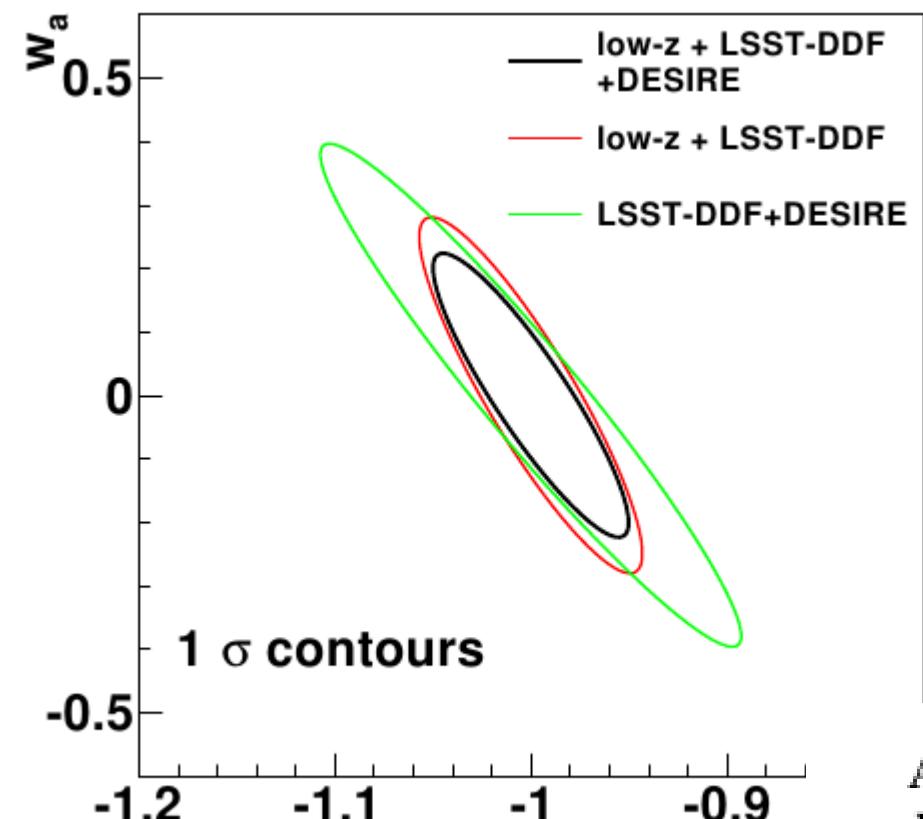
- $O(10,000)$ supernovae
- In \sim a few months of telescope time.

	z_{min}	z_{max}	area (deg 2)	duration (months)	events
DESIRE	0.75	1.55	10	2x6	1740
LSST-DDF	0.15	0.95	50	4x6	8800
Low z	0.05	0.35	3000	6	8000



(Astier et al, in prep)

LSST + EUCLID : EXPECTED CONSTRAINTS



(Astier et al, in prep)

Note : requires acquiring redshifts



Assumptions			$\sigma(w_a)$	z_p	$\sigma(w_p)$	FoM
cal	evo	train				
n	n	n	0.15	0.30	0.016	418
y	n	n	0.18	0.30	0.016	339
n	y	n	0.18	0.25	0.018	315
y	y	n	0.20	0.27	0.019	266
y	n	y	0.21	0.28	0.020	238
y	y	y	0.22	0.25	0.022	203

CONCLUSION

- Hubble diagrams with $O(1000)$ SNe Ia
- Best measurements of w to date (6%)
- No tensions with Planck / Λ CDM
- But : still dominated by systematics
 - Calibration
 - Astrophysics (?)
- Progress possible from :
 - High stat + IR + syst control
 - Understanding SN Ia / SN progenitor / environment